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MONITORING DISPOSAL-WELL SYSTEMS

General Electric Company

PREPARED FOR
Environmental Monitoring and Support Laboratory

July 1975

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Environmental Monitoring Series

MONITORING DISPOSAL-WELL SYSTEMS

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by

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ENVIRONMENTAL MONITORING AND SUPPORT LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
LAS VEGAS, NEVADA 89114

Effective June 29, 1975 the National Environmental Research Center–Las Vegas "NERC–LV" was designated the Environmental Monitoring and Support Laboratory–Las Vegas "EMSL–LV." This Laboratory is one of three Environmental Monitoring and Support Laboratories of the Office of Monitoring and Technical Support in the U.S. Environmental Protection Agency's Office of Research and Development.

ABSTRACT

The U.S. Environmental Protection Agency is required, under P.L. 92-500, the Federal Water Pollution Control Act Amendments of 1972, to establish a system for the surveillance of the quality of the nation's surface and ground waters. Enactment of P.L. 93-523, the Safe Drinking Water Act, further requires that State programs in order to be approved, shall include monitoring programs to prevent underground injection which endangers drinking water sources. This report provides information concerning the data needed for monitoring the subsurface injection of wastewater through cased disposal wells, and discusses the methods and tools available for obtaining the data. The procedures for using the data for predicting the response of the receiving aquifer to injection are then outlined. Surveillance of operating disposal wells is reviewed. Numerous examples are given throughout the text.

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SECTION I

CONCLUSIONS

The subsurface environment is a complex one characterized by the rocks and their structure, lithology, contained fluids and other resources, and mechanical properties. The static and dynamic states of the rocks and fluids are also characteristic of a region and a specific location.

An estimate of the characteristics of the subsurface environment can be made prior to drilling of a well based on projections of data from outcrops, previously drilled wells, and possibly surface geophysical studies. A much more accurate knowledge of the local subsurface environment is obtained when a well is drilled and tested. Data obtained from a well are based on rock and fluid samples, geophysical logs, and pumping or injection tests.

When the characteristics of the subsurface environment have been estimated or determined, the response to wastewater injection can be predicted. Such predictions are essential to monitoring because they provide a baseline of expected performance, including rate of pressure buildup and rate and direction of travel of injected wastewater.

The principal means of injection-well monitoring is of the injection well itself. This provides more protection than is commonly realized, because the well is, in most cases, the most likely source of escape of injected wastewater. Periodic inspection and testing of injection well facilities complements continuous monitoring of well performance and should prove helpful in detecting deterioration of these facilities prior to failure.

Monitoring wells can be used for several purposes; they may be constructed in the injection aquifer, in or just above the confining beds, or in freshwater aquifers. Local geology and hydrology, the waste being injected, and economics are factors in determining if monitor wells are needed, and, if so, how many and where.

Other types of monitoring include surface geophysics, sampling of springs, streams, and lakes, and monitoring to record any seismic events which might be related to operation of the injection well.

SECTION II

RECOMMENDATIONS

Monitoring of subsurface wastewaters injection should be thought of as the full spectrum of consideration given to determining the effects of a wastewater injection system from planning of the system through well construction, testing, operation, and abandonment.

Policy guidelines of the Environmental Protection Agency and of The Ohio River Valley Water Sanitation Commission (ORSANCO) should be used as a basis for injection well monitoring. These sources also provide suggestions for a suitable data base for monitoring and ORSANCO outlines a series of administrative procedures that should be followed.

This publication provides a discussion of the tools and methods for obtaining the needed data base and of the use of the resulting subsurface data for prediction and interpretation of well behavior during operation. It also discusses the surveillance of operating wells in some detail. The maximum use should be made of the methods and tools that are available consistent with the practicalities of available resources. Because of the obvious complexity of many of the tools and methods, regulatory agencies should not hesitate to request the assistance of other public agencies and of private consultants in monitoring injection systems.

SECTION III

INTRODUCTION

As of mid-1973, at least 278 industrial wastewater injection wells had been constructed and 61 percent of them were operating (Warner and Orcutt, 1973). This is a relatively small number of waste disposal units, but the number has continued to increase at a rate of about 30 wells annually and could increase even more rapidly in response to the objective of eliminating discharge to surface waters and in response to demands of new technologies such as geothermal energy production, desalination, and radioactive waste disposal. Regardless of the number of industrial wastewater injection wells, they have been an object of unusual attention by regulatory agencies and by environmentalists.

This attention is reflected by inclusion of specific references to disposal wells in Public Law 92-500, the Federal Water Pollution Control Act Amendments of 1972. A provision of that Act is the requirement that the Administrator of the Environmental Protection Agency shall, in cooperation with the States or other Federal agencies, establish a system for the surveillance of the quality of surface waters and ground waters. The enactment of Public Law 93-253, the Safe Drinking Water Act, further requires the Administrator to propose and promulgate for State underground injection programs minimum monitoring requirements to assist in preventing underground injection which endangers drinking water sources.

This publication provides technical information concerning data needed for monitoring and the methods and tools available for monitoring of wastewater injection wells and examples of their application. However, the material presented cannot be expected to satisfy the monitoring requirements of all aspects of underground fluid injection that will likely be included in the rules and regulations that are promulgated in response to P. L. 93-523. The definition of the term underground injection is sufficiently broad in P. L. 93-253 to include subsurface emplacement of fluids by many means, such as ponds, pools, lagoons, and pits. This publication relates specifically to the subsurface emplacement of fluids through cased disposal wells.

To some, monitoring of groundwater is often thought of as the observation of groundwater quality by sampling of wells and springs. In this publication, monitoring is meant to include the full spectrum of consideration given to determining the effects of wastewater injection systems, from planning of the system through well construction, testing, operation, and finally abandonment. The policy of the Environmental Protection Agency is consistent with this approach (see Appendix; also, Hall and Ballantine, 1973). ORSANCO (Ohio River Valley Water Sanitation Commission, 1973) also has established a basis for injection well monitoring. Both the EPA policy statement and the ORSANCO publication provide suggestions for a suitable data base for monitoring. ORSANCO also suggests a series of administrative procedures, which, if followed, assure the early involvement of regulatory agencies in monitoring and provide for their continued surveillance of injection systems throughout construction, use, and abandonment.

This publication is intended to complement existing ones, such as those mentioned above, by providing a more extensive discussion of the data that characterize the subsurface environment, of how these data are obtained, and of how they are used to predict and interpret injection well response. The surveillance of operating injection wells is also treated in more detail here than in earlier publications.

SECTION IV

THE SUBSURFACE ENVIRONMENT

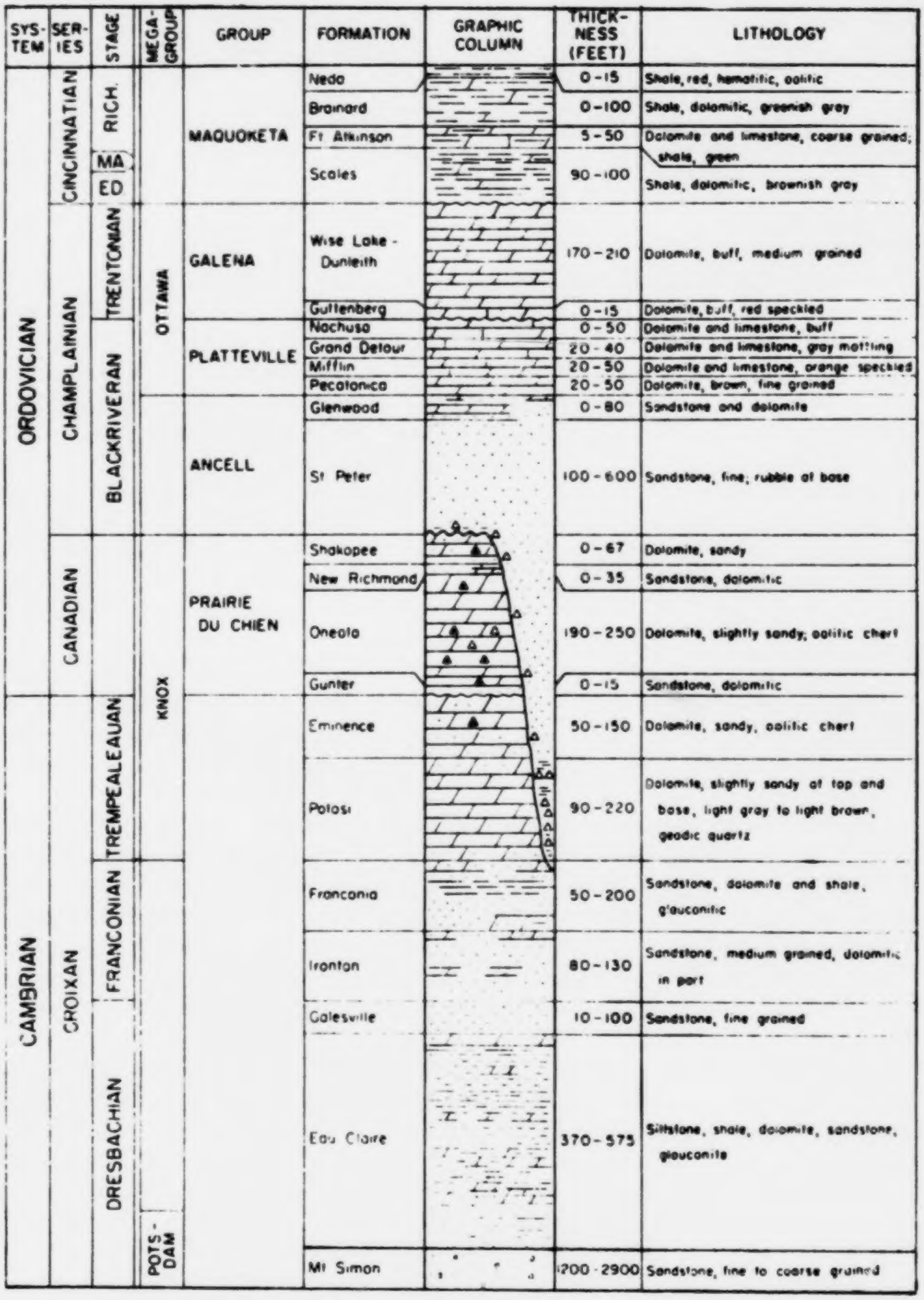
In devising a monitoring program for a wastewater injection system, the first consideration is definition of the regional and local subsurface environment. Factors in such an appraisal are stratigraphic and structural geology, lithology, fluid properties, mechanical properties of injection and confining units, hydrodynamics, and subsurface resources. Other publications (Warner, 1965 and 1968) have reviewed, in general, the relation of the subsurface environment to wastewater injection. The purpose of the following discussion is to provide more specific detail and examples of the methodology for applying these concepts to monitoring. It will be attempted, insofar as possible, to avoid repetition of material that has been previously presented.

STRATIGRAPHIC GEOLOGY

Regional stratigraphy is determined by use of outcrop and borehole data which have been interpreted and are generally presented in the form of columnar sections, isopach maps, facies maps, and cross sections.

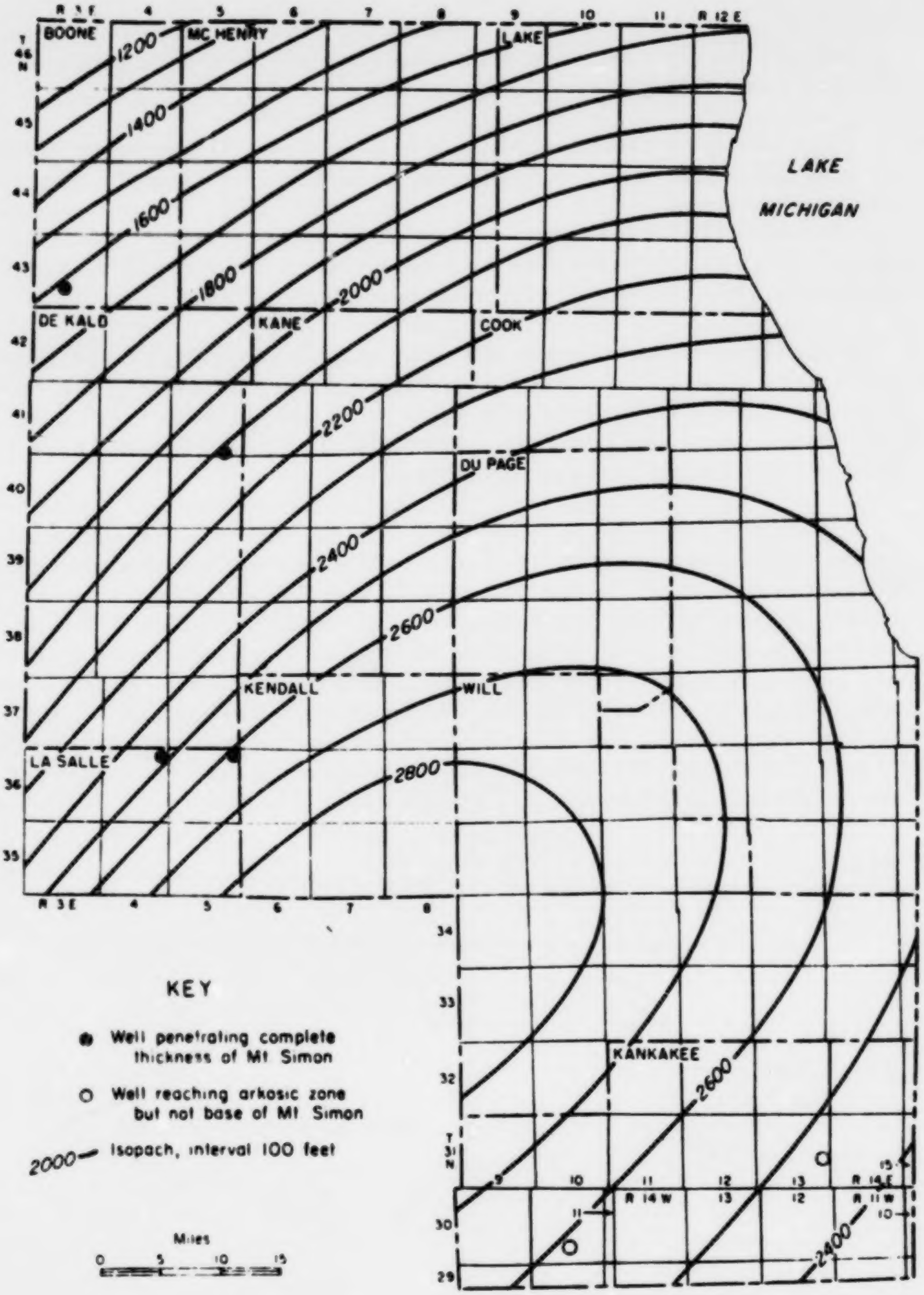
The basic data unit used in studies of stratigraphic geology is the columnar section, which is a graphic representation of the sequence, thickness, lithology, and relationship of the rock units at a location. A generalized columnar section may be prepared, which shows these parameters for a region. Figure 1 is a generalized columnar section for northeastern Illinois. Columnar sections are prepared by using cores, cuttings, and geophysical logs from boreholes and, where outcrops are present, from them. Some possible injection horizons in Figure 1 are the St. Peter, Ironton, Galesville, and Mt. Simon Formations. Of these, the Mt. Simon is the deepest, and can be seen to be overlain by the Eau Claire Formation, which may contain confining shale beds. On the other hand, the St. Peter Formation is shallower and is overlain by limestones and dolomites which are less dependable as aquitards; and, therefore, the St. Peter has a lesser potential for wastewater injection.

Isopachous maps indicate, by contour lines, the varying thickness of a stratigraphic unit. Figure 2 is an isopachous map of the Mt. Simon Formation in Illinois, showing that this sandstone unit varies in thickness



SYSTEM	SERIES	STAGE	MEGAGROUP	GROUP	FORMATION	GRAPHIC COLUMN	THICKNESS (FEET)	LITHOLOGY
ORDOVICIAN	CINCINNATIAN	RICH.	OTTAWA	MAQUOKETA	Nedo		0-15	Shale, red, hematitic, oolitic
					Brainard		0-100	Shale, dolomitic, greenish gray
					Ft Atkinson		5-50	Dolomite and limestone, coarse grained; shale, green
		MA ED			Scales		90-100	Shale, dolomitic, brownish gray
	CHAMPLAINIAN	TRENTONIAN		GALENA	Wise Lake - Dunleith		170-210	Dolomite, buff, medium grained
					Guttenberg		0-15	Dolomite, buff, red speckled
		BLACKRIVERAN		PLATTEVILLE	Nachusa		0-50	Dolomite and limestone, buff
					Grand Detour		20-40	Dolomite and limestone, gray mottling
					Mifflin		20-50	Dolomite and limestone, orange speckled
					Pecatonica		20-50	Dolomite, brown, fine grained
				ANCELL	Glenwood		0-80	Sandstone and dolomite
					St Peter		100-600	Sandstone, fine; rubble at base
	CANADIAN		KNOX	PRAIRIE DU CHIEN	Shakopee		0-67	Dolomite, sandy
					New Richmond		0-35	Sandstone, dolomitic
					Oneota		190-250	Dolomite, slightly sandy; oolitic chert
					Gunter		0-15	Sandstone, dolomitic
CAMBRIAN	CROIXAN	TREMPEALEAUAN			Eminence		50-150	Dolomite, sandy, oolitic chert
					Potosi		90-220	Dolomite, slightly sandy at top and base, light gray to light brown, geodic quartz
		FRANCONIAN			Franconia		50-200	Sandstone, dolomite and shale, glauconitic
					Ironton		80-130	Sandstone, medium grained, dolomitic in part
		DRESBACHIAN			Galesville		10-100	Sandstone, fine grained
					Eau Claire		370-575	Siltstone, shale, dolomite, sandstone, glauconite
			POTSDAM		Mt Simon		1200-2900	Sandstone, fine to coarse grained

Figure 1. Generalized columnar section of Cambrian and Ordovician strata in northeastern Illinois (Buschbach, 1964, p. 16).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15
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KEY
Well penetrating complete thickness of Mt. Simon
Well reaching arkosic zone but not base of Mt. Simon
2000 Isopach, interval 100 feet
Miles
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Figure 2. Isopach map of Mt. Simon Formation in northeastern Illinois (Buschbach, 1964).

from 0 to over 2,000 feet within that State. Other factors being equal, locations where the Mt. Simon Formation is thickest have greatest potential for wastewater injection.

The facies of a stratigraphic unit are its laterally varying aspects, such as lithology, fossil content, and so forth. For example, the Eau Claire Formation, which overlies the Mt. Simon Formation, consists of a mixture of siltstone, shale, dolomite, and sandstone in northeastern Illinois (Figure 1), but passes by facies change eastward into sandstone in central Ohio and to dolomite in eastern Ohio (Figure 3).

Some types of facies maps are ratio maps, percentage maps, and isolith maps. These facies maps are different ways of showing the relative amounts of the various lithologies in a rock unit or units. The ratio and percentage maps show contours of the ratios or percentages of the aggregate thicknesses of lithologic classes.

Figure 4 is a lithologic ratio map, showing the relative ratios of sandstone, shale, and dolomite in post-Mt. Simon pre-Knox rocks in Ohio. This figure generally shows that this group of rocks changes from a sandy facies in western Ohio to a dolomite facies in eastern Ohio. The rocks depicted in Figure 4 are equivalent to the Eau Claire Formation in Figure 1. So, in eastern Ohio, the Eau Claire Formation is almost entirely dolomite, rather than the mixed lithology shown in Figure 1. Without further information, Figures 3 and 4 indicate that the Eau Claire Formation becomes less promising as a confining unit for the Mt. Simon Formation as it is traced eastward from Illinois into Ohio.

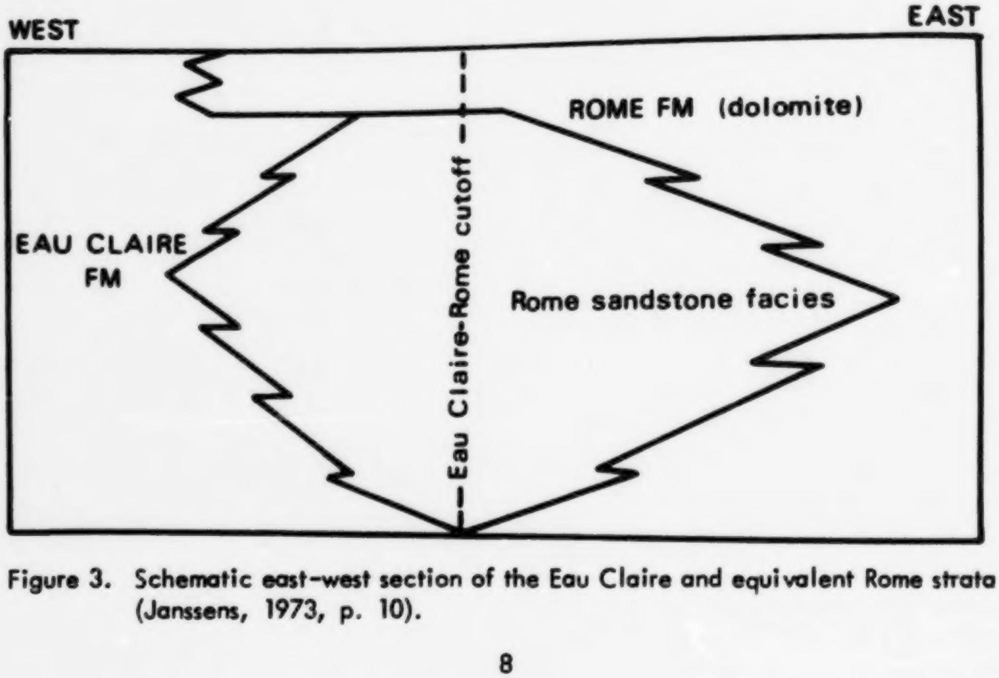
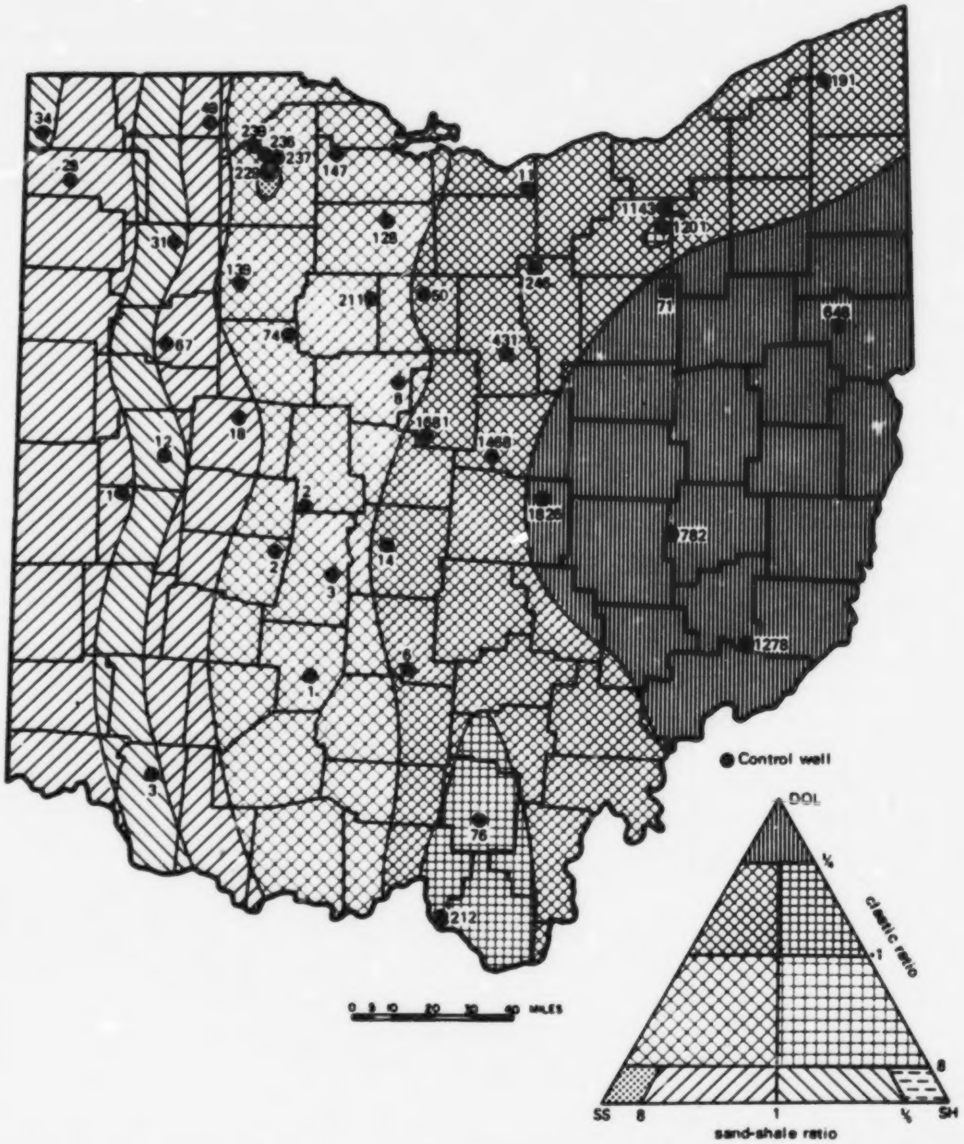


Figure 3. Schematic east-west section of the Eau Claire and equivalent Rome strata (Janssens, 1973, p. 10).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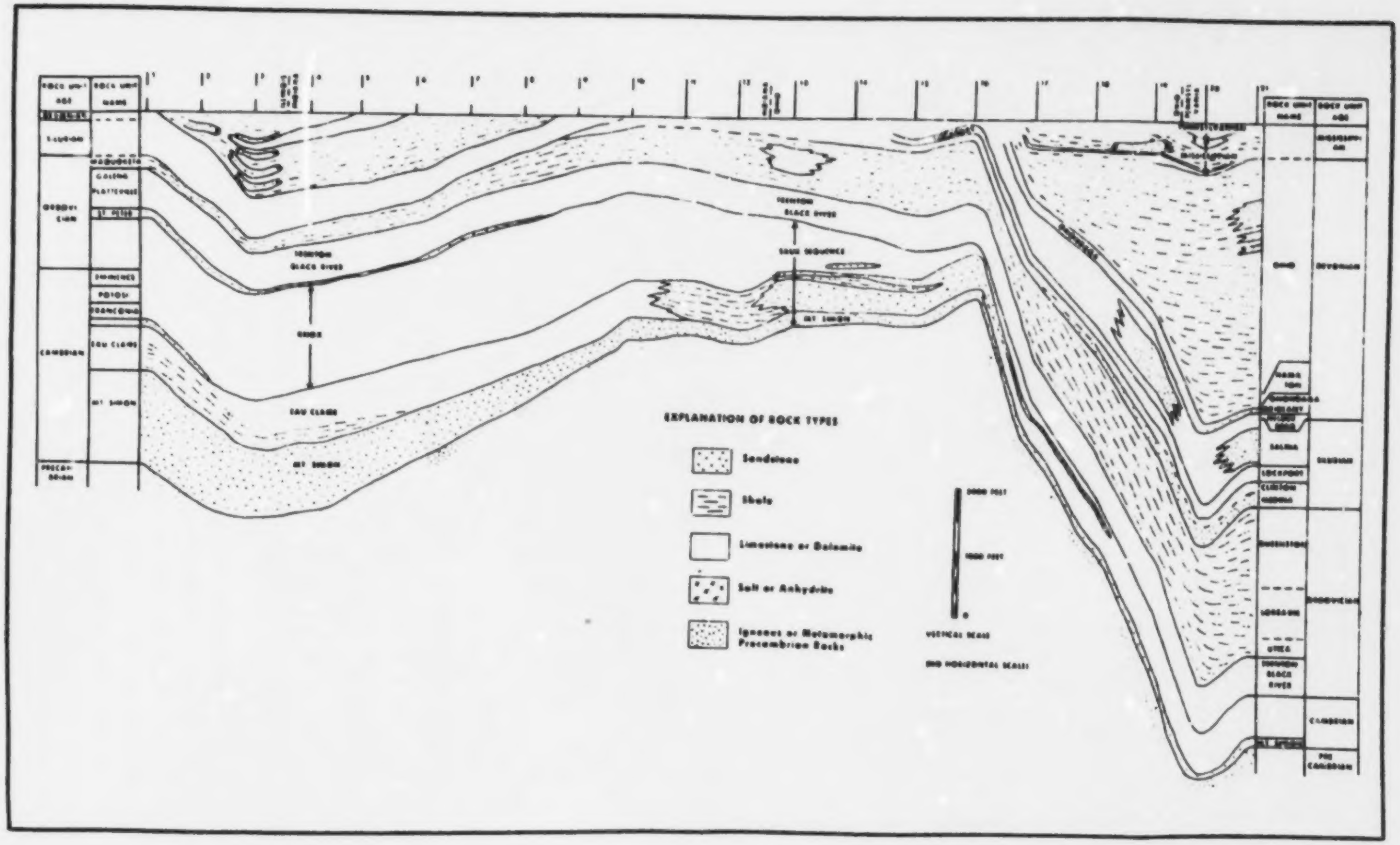
sand-shale ratio

Figure 4. Lithologic ratio map of post-Mt. Simon pre-Knox rocks (Janssens, 1973, p. 19).

Figure 5 is an east-west cross section of Paleozoic rocks extending from east-central Illinois to northwestern Pennsylvania. This cross section shows the facies changes in the Eau Claire that are described above and shown in earlier figures. The cross section also shows that the Mr. Simon Formation is about 1,500 feet thick in east-central Illinois, but thins to about 100 feet across northern Ohio and into northwestern Pennsylvania. Thus, much of the same information conveyed in the previous figures is summarized in a readily understandable form in such a cross section.


ROCK UNIT AGE
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MT SIMON
TRENTON BLACK RIVER
KNOX
OHIO
DEVONIAN
SALINA
LOCKPORT
UTICA
PRE CAMBRIAN
EXPLANATION OF ROCK TYPES
Sandstone
Shale
Limestone or Dolomite
Salt or Anhydrite
Igneous or Metamorphic Precambrian Rocks
2000 FEET
1000 FEET
0
VERTICAL SCALE
AND HORIZONTAL SCALES

Figure 5. East-west cross section of Paleozoic rocks in the northern Ohio River Valley — modified after cross sections in American Association of Petroleum Geologists cross section Publication 4, 1966 (Ohio River Valley Water Sanitation Commission, 1973, p. 51).

Local stratigraphy is first projected from regional data before drilling of a well, then determined in detail for the well when it is drilled. As previously mentioned, the means of displaying the stratigraphy of a well is the columnar section.

STRUCTURAL GEOLOGY

Structural geology means the folding, faulting, and fracturing of rocks and the geographic distribution of these features. One means of showing regional structural geologic features is a map which includes areas or lines of major features. Figure 6 is such a map for the Ohio River Basin. Another type of map is the structural contour map. Figure 7 is a structural contour map on the top of the Mt. Simon Formation in Illinois. Such a map allows an estimate of the approximate depth to the mapped unit and shows the location of known faults and folds that may influence decisions concerning the location and monitoring of an injection well.

LITHOLOGY

Lithology refers to the composition and texture of a rock. The generalized columnar section in Figure 1 contains brief, highly generalized lithologic descriptions of rock units in northeastern Illinois. The descriptions prepared for individual wells are very detailed. An example of a description of a core from the top of the Mt. Simon Formation in one well is shown in Table 1.

Table 1. Typical description of a core from the top of the Mt. Simon Formation in Illinois.

Depth in Well	Lithologic Description
3019.4 - 3020.5	Sandstone; grayish-white; medium to very coarse grained; grains are broken, pitted, and chipped; very cohesive and hard; very tight; semi-quartzitic.
3020.5 - 3021.8	Sandstone; as above; very poor sorting; medium to very coarse, rounded grains, with abundant fine-grained matrix; glassy; slightly pyritic; cohesive and hard; not as tight as above zone; limited mud invasion.
3021.8 - 3023.8	Sandstone; good sorting; very fine to fine, subangular grains; slightly pyritic; cohesive and firm; limited mud invasion; very few shale laminations.

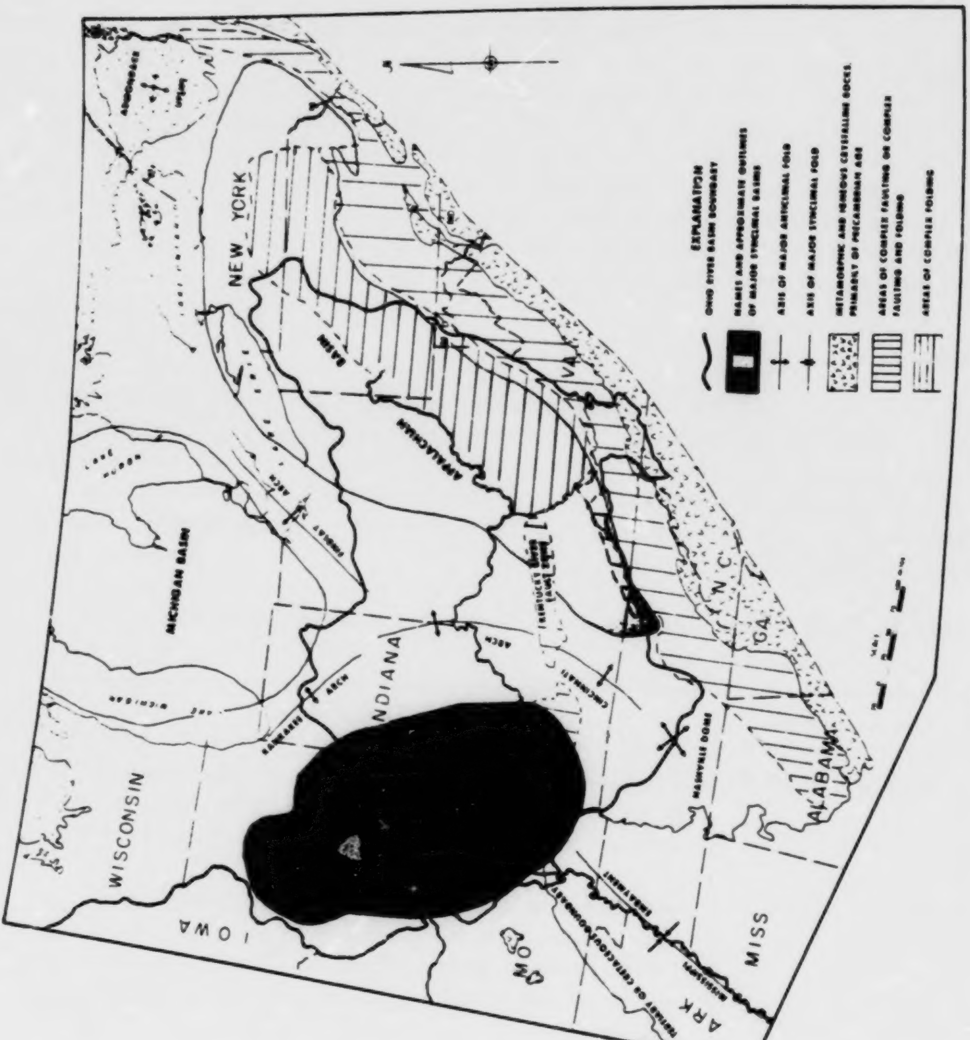
EXPLANATION
IOWA
WISCONSIN
MICHIGAN BASIN
INDIANA
NEW YORK
APPALACHIAN
BASIN
VA
N.C.
GA
ALABAMA
MISS
ARK
MO

Figure 6. Map of the Ohio River Basin and vicinity showing some major geologic features. Data modified from published maps (Ohio River Valley Sanitation Commission, 1973, p. 24).

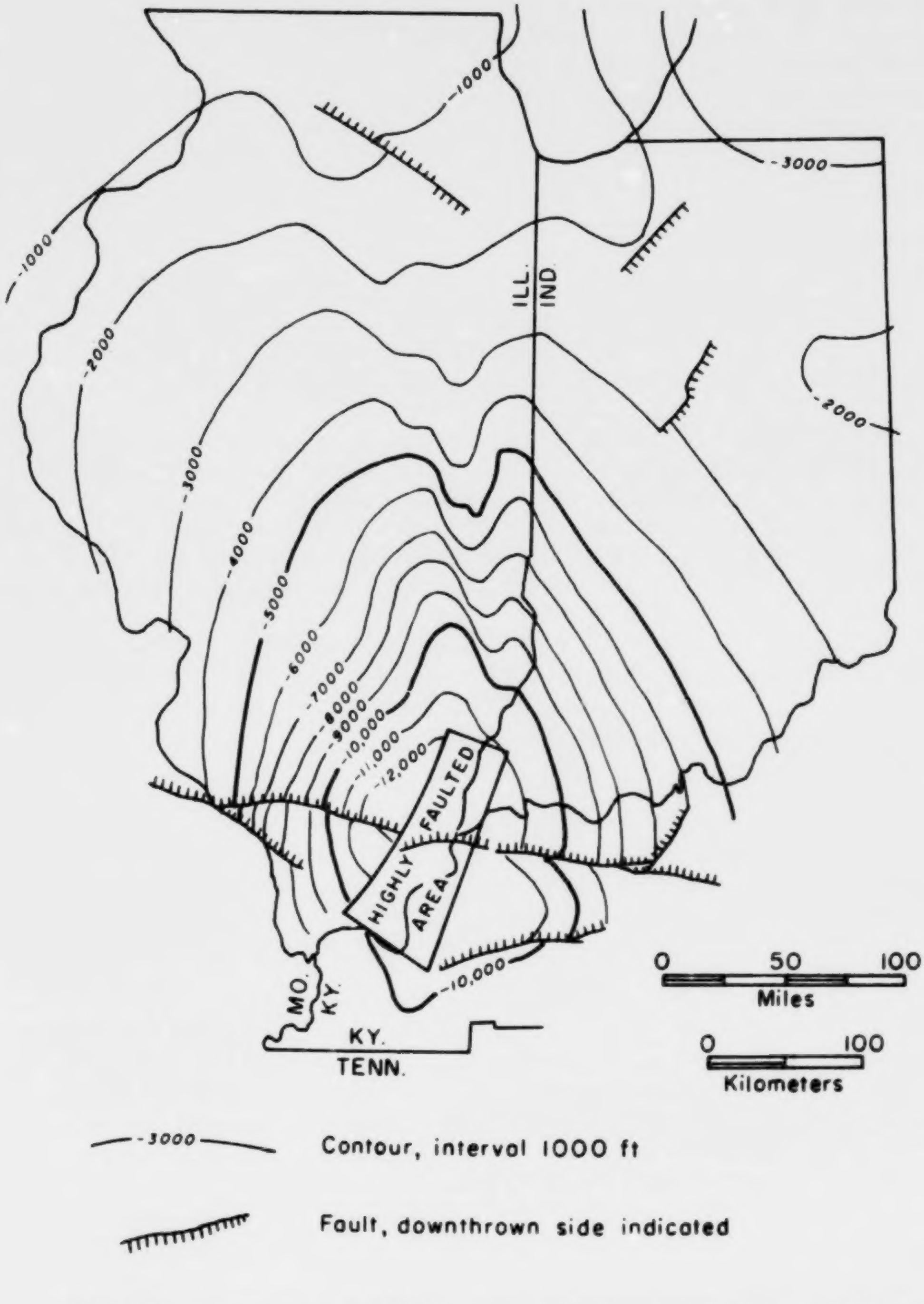
-1000
-1000
-3000
-2000
-2000
ILL.
IND.
-3000
-4000
-5000
-6000
-7000
-8000
-9000
-10,000
-11,000
-12,000
HIGHLY FAULTED AREA
-10,000
MO.
KY.
KY.
TENN.
0
50
100
Miles
0
100
Kilometers
-3000
Contour, interval 1000 ft
Fault, downthrown side indicated

Figure 7. Structure on top of Mt. Simon Formation (Bond, 1972, p. 36).

Such detailed descriptions are prepared from cores, cuttings, and geophysical logs, and are necessary for determining the rock-unit characteristics in a test well. From such descriptions, and other data, injection intervals, confining beds and casing points are selected and other engineering decisions are made.

FLUIDS

Chemistry

Judgment as to whether wastewater may or may not be permitted to be injected into a rock unit depends, in part, on the chemistry of the aquifer water. The chemistry of aquifer water is also important because of the possibility of reactivity with injected wastewater.

Policy concerning the minimum salinity of water in aquifers approved for wastewater injection varies by State. In the Ohio Valley region, Illinois agencies have determined that groundwater containing less than 10,000 mg/liter total dissolved solids should be protected. In New York, waste injection is prohibited in aquifers with a dissolved solids content of 2,000 mg/liter or less. In Florida, the limiting value is 1,500 mg/liter.

The problem of potential reactivity between wastewater and aquifer minerals and water is summarized by Warner (1968). Several recent papers concerning this topic are contained in the Proceedings of the Symposium on Underground Waste Management and Environmental Implications (Cook, 1972).

In order to evaluate the details of the chemistry of aquifer water, it is necessary to obtain samples after a well is drilled; samples from previously drilled wells may provide a good indication of what will be found. Geophysical logs are also useful for estimating the dissolved solids content of aquifer water in intervals that are not sampled, as will be discussed later.

In Illinois, the Mt. Simon Formation has been found to contain water ranging in dissolved solids content from less than 1,000 mg/liter in the northern part of the State to over 300,000 mg/liter in the southern part. Such information can be displayed in the form of an isocon map (Figure 8). Most of the dissolved solids are sodium chloride, but significant amounts of calcium, magnesium, and sulfate are also present (Table 2).

Viscosity

Viscosity is the ability of a fluid to resist flow, and is an important property in determining the rate of flow of a fluid through porous media.

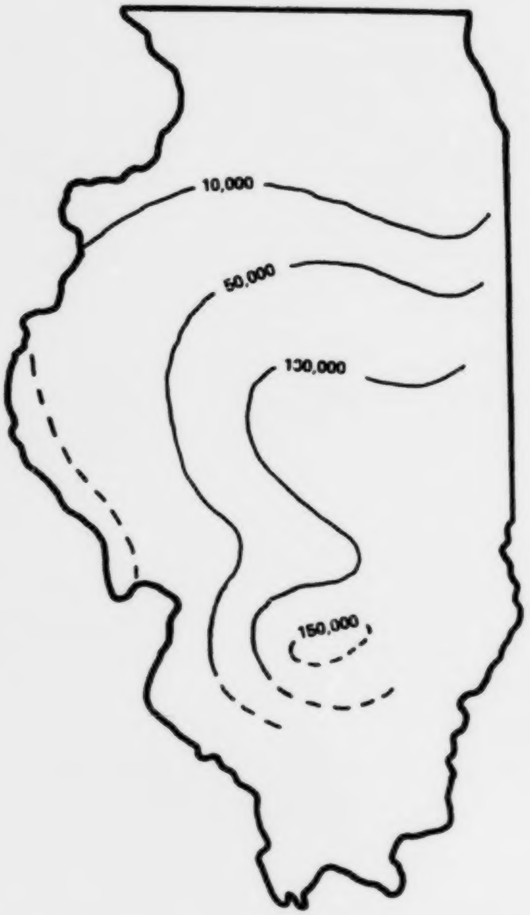

Figure 8. Isocon map, showing the dissolved solids content in parts per million of water in the upper 100 feet of the Mt. Simon Formation in Illinois.

The common unit of viscosity is the poise, or the centipoise, which is one one-hundredth of a poise. Figure 9 shows the variation in viscosity of water with temperature and salinity. Both temperature and dissolved solids content can have a significant effect. In most cases, the effects will be offsetting in subsurface waters, since temperature and dissolved solids content both tend to increase with increasing depth. The viscosity of some wastewaters may be unusually high as a result of the presence of dissolved organic chemicals. Pressure in the range of interest has an insignificant effect on viscosity.

Table 2. Analysis of water from the Mt. Simon Formation in the vicinity of Bloomington, Illinois.

Analysis	Result
Specific gravity	1.050
pH	6.6
Hydrogen sulfide	0.0 mg/liter
Carbonate alkalinity	0.0 mg/liter
Bicarbonate alkalinity	68 mg/liter
Chlorides	39,250 mg/liter
Total hardness	17,900 mg/liter
Calcium	5,200 mg/liter
Magnesium	1,190 mg/liter
Sulfates	1,700 mg/liter
Manganese	1.3 mg/liter
Total iron	27.0 mg/liter
Total dissolved solids (calculated)	65,460 mg/liter

Density

The density of a fluid is its mass per unit volume. The density of a liquid increases with increased pressure and decreases with increased temperature. However, the density of water changes very little within the range of pressures and temperatures of interest. For example, the density of water decreases only 0.04 gm/cm^3 between 60°F and 210°F (Figure 10), and increases only about 0.04 gm/cm^3 from 0 to 14,000 psi (Figure 11). A more important influence on the density of water is the total dissolved solids content. Figure 12 shows the effect of various amounts of sodium chloride on specific gravity (or density).* Since natural brines may differ significantly from sodium chloride solutions, it may be desired to develop empirical relationships between density and dissolved solids as was done by Bond (1972) for the Illinois basin (Figure 13).

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*Specific gravity is the ratio of the mass of a body to that of an equal volume of pure water, so for practical purposes, the numerical values of density and specific gravity are equal. Specific gravity, however, is is dimensionless.

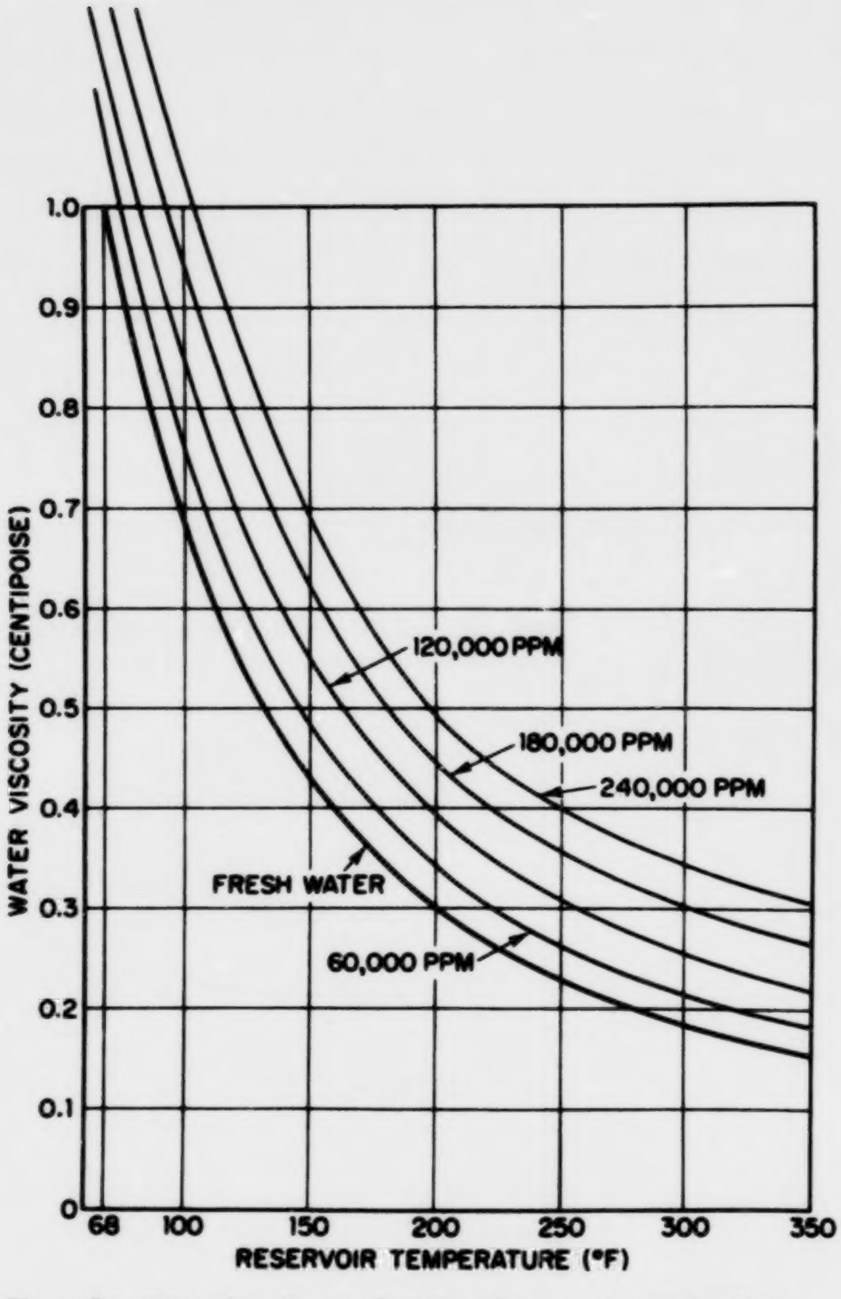

Figure 9. Water viscosity as a function of temperature and salinity (ppm NaCl) (Pirson, 1963, p. 40).

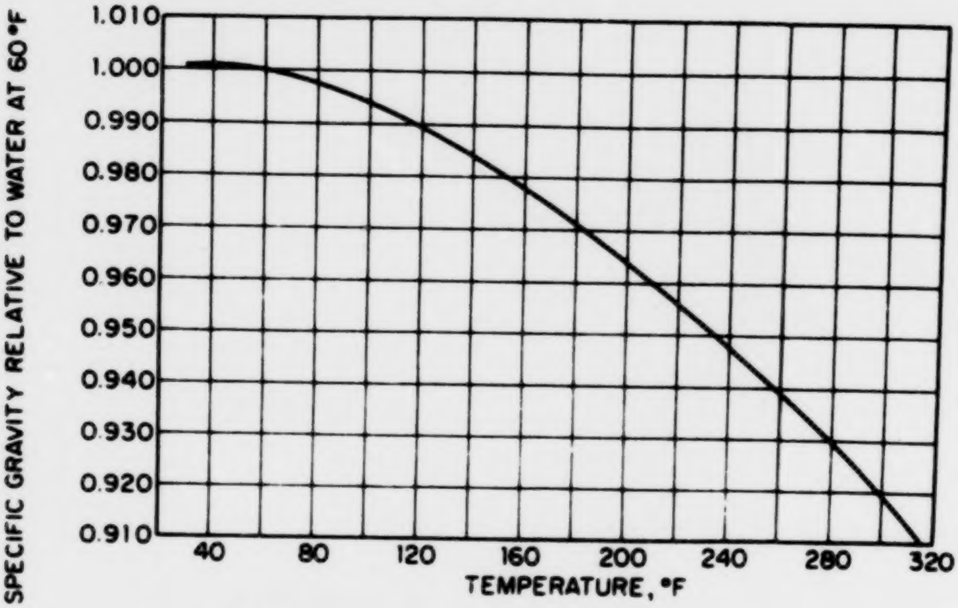

Figure 10. Specific gravity of distilled water as a function of temperature (Pirson, 1963, p. 39).

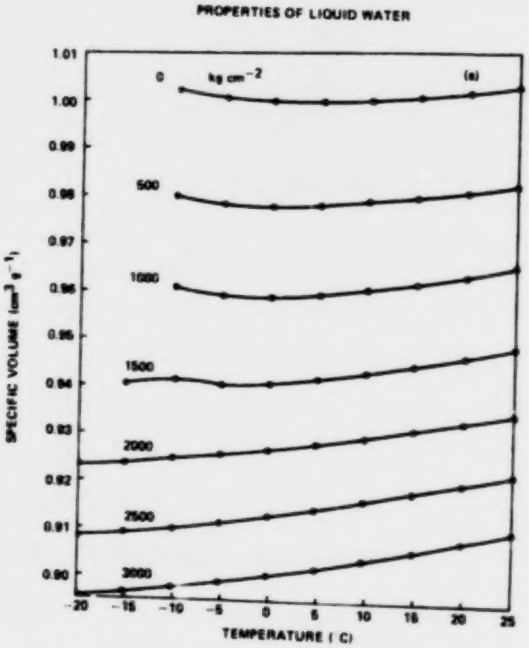

Figure 11. Specific volume of water as a function of temperature and pressure (Eisenberg and Kauzmann, 1969, p. 186).

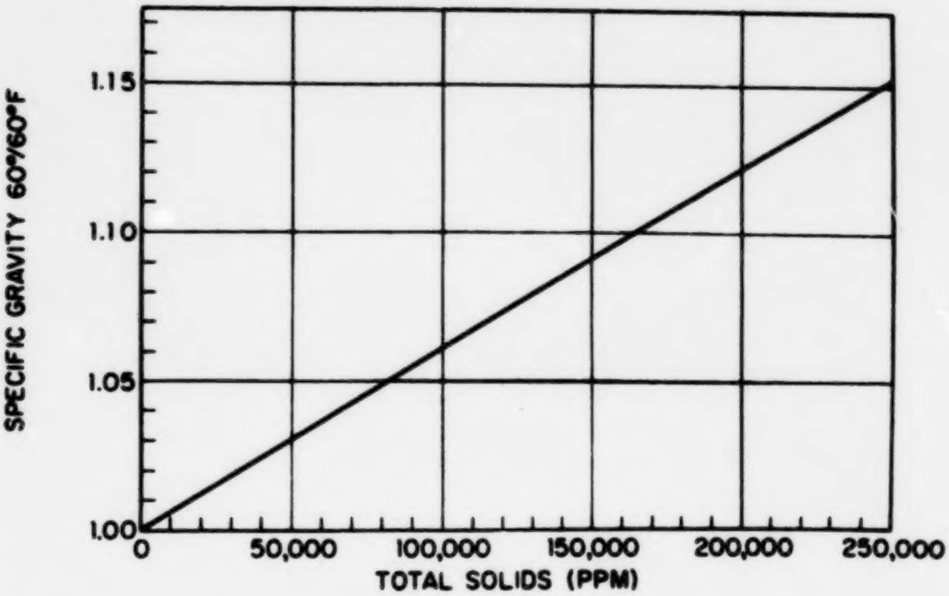

Figure 12. Specific gravity of formation waters (D_w) versus total solids in ppm (data for NaCl solutions) (Pirson, 1963, p. 39).

Pressure

A knowledge of fluid pressure in the unit proposed for wastewater injection is important. Fluid pressure can be measured directly in the borehole at the depth of the injection horizon, usually by performing a drill-stem test, which will be described later. Fluid pressure at the injection horizon can also be measured indirectly by determining the static water level in the borehole, then computing the pressure of the fluid column at the depth of interest.

Figure 14 shows how fluid pressure increases with depth in a well bore filled with freshwater with a specific gravity of 1.0. When the average specific gravity of the water or wastewater is other than 1.0 the rate of pressure increase varies accordingly. For example, if a well bore is filled with formation water with a dissolved solids content of 65,000 mg/liter and a specific gravity of 1.05, then fluid pressure increases at a rate of 0.455 psi/ft, and would be 455 psi at the bottom of a 1,000-ft-deep water-filled well. The fluid pressure must be added to the pump pressure in injection calculations to determine the total pressure.

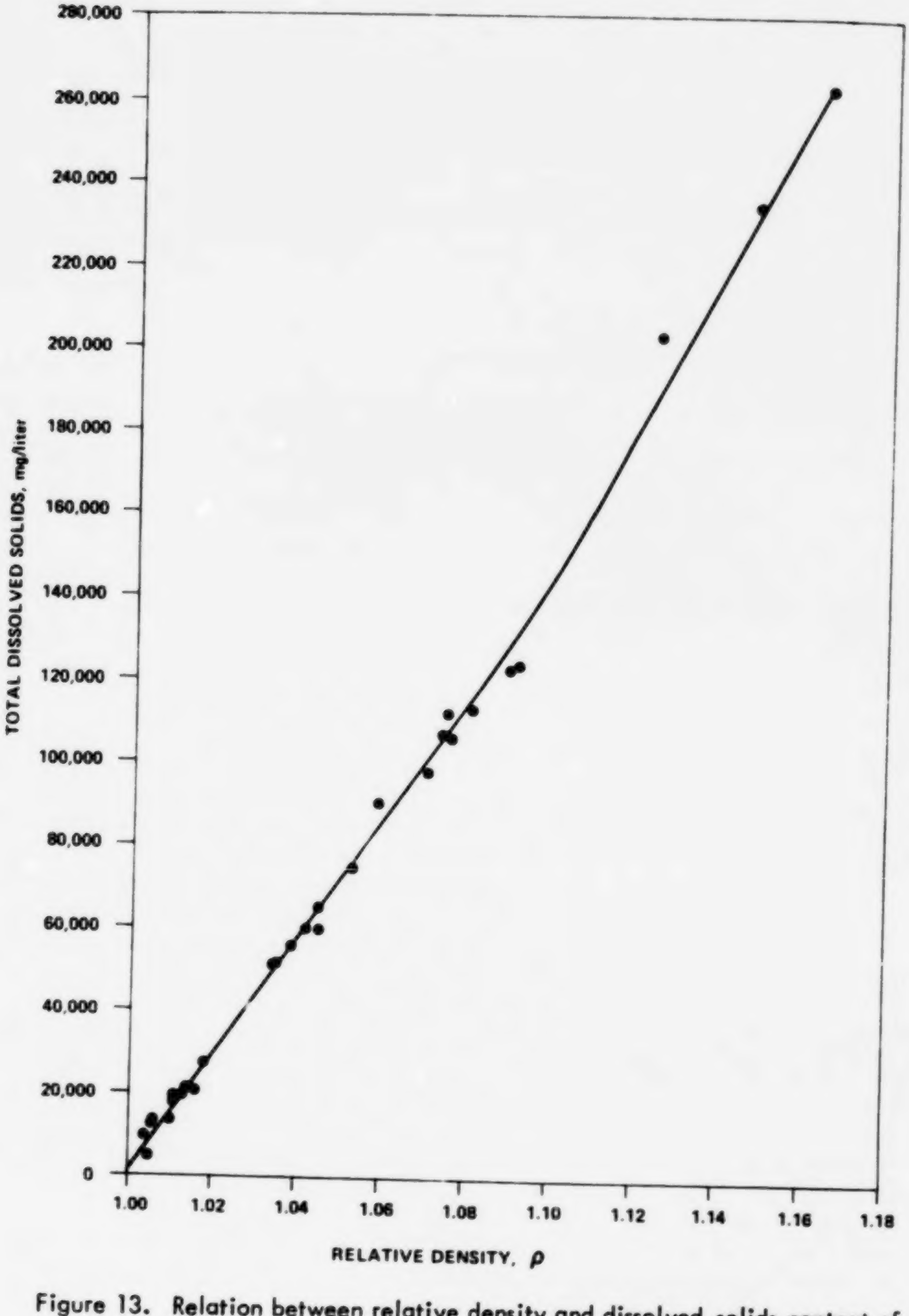

Figure 13. Relation between relative density and dissolved solids content of brines in deep aquifers of the Illinois basin (Bond, 1972).

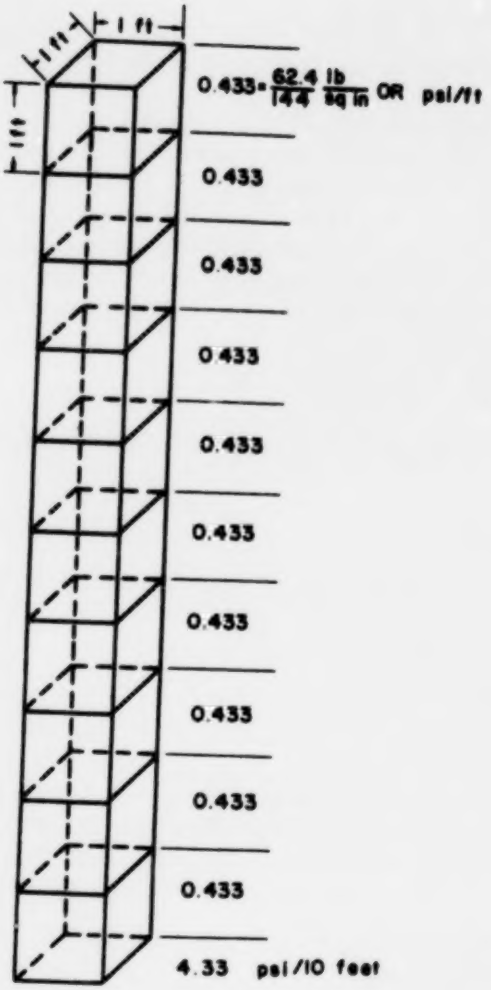
1 ft
1 ft
1 ft
0.433 = 62.4/144 lb/sq in OR psi/ft
0.433
0.433
0.433
0.433
0.433
0.433
0.433
0.433
0.433
4.33 psi/10 feet

Figure 14. Hydraulic pressure gradient in a column of water (Katz and Coats, 1968, p. 11).

Although instances of truly anomalous formation pressure are likely to be relatively rare at sites selected for wastewater injection, the existence of unusually high or low pressures and the possible reasons for their existence should be recognized. Some causes of anomalous pressure are:

1. Compaction of sediments
2. Tectonic forces

3. Osmotic effects
4. Massive extraction or injection of fluids.

Abnormally high pressures can result from 1, 2, and 3 and from massive injection. Abnormally low pressures can result from osmotic effects and extraction of fluids. Abnormally high pressures resulting from compaction of sediments are common in deep wells of the Gulf Coast (Dickinson, 1953). Berry (1973) concluded that abnormally high pressures in the California Coast Ranges are a result of tectonic forces. Hanshaw (1972) discussed natural osmotic effects and their relation to subsurface wastewater injection.

Compressibility

The compressibility of an elastic medium is defined as:

$$\beta = \frac{-\partial V}{V \partial p} \qquad (F/L^2)^{-1} \tag{1}$$

where β = compressibility of medium (pressure^{-1})
V = volume
p = pressure .

with dimensions

F = force
L^2 = area.

The compressibility of water varies both with temperature and pressure, as is shown in Figure 15. For problems in wastewater injection, β will generally be within the range of 2.8 to 3.3×10^{-6} psi^{-1}, and 3.0×10^{-6} psi^{-1} is a reasonable value to assume in most cases.

MECHANICAL PROPERTIES OF INJECTION AND AND CONFINING UNITS

Porosity

Porosity is defined as:

$$\phi = \frac{V_v}{V_t} \qquad \text{(dimensionless)} \tag{2}$$

where ϕ = porosity, expressed as a decimal fraction
V_v = volume of voids
V_t = total volume of rock sample.

Porosity is also commonly expressed as a percentage. Porosity may be total porosity or effective porosity. Total porosity is a measure of all void space. In comparison with total porosity, effective porosity is

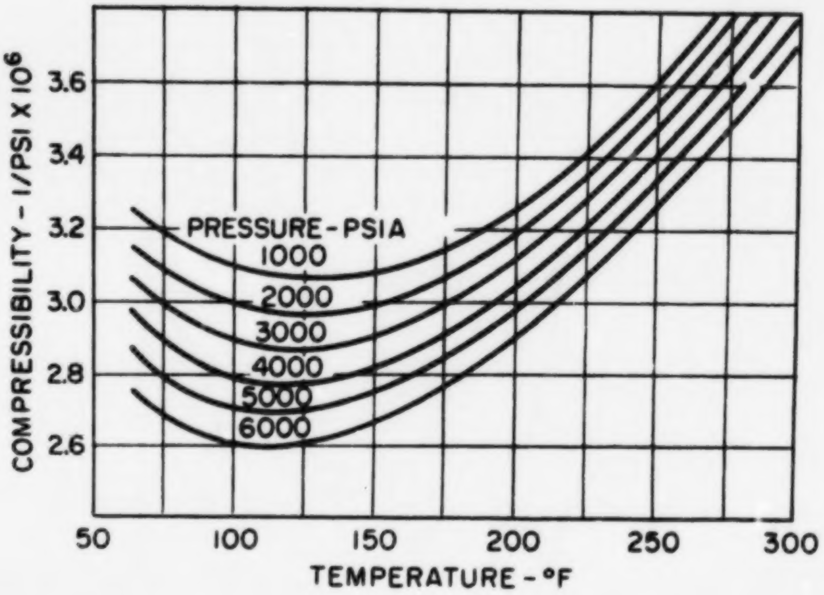

Figure 15. Compressibility of water (Katz and Coats, 1968, p. 93).

based on the total volume of interconnected voids. Effective porosity better defines the hydraulic properties of a rock unit, since only interconnected porosity is available to fluids flowing through the rock. In the remainder of the report, reference to porosity implies effective porosity unless otherwise stated.

Porosity may also be classified as primary or secondary. Primary porosity includes original intergranular or intercrystalline pores and the porosity associated with fossils, bedding planes, and so forth. Secondary porosity results from fractures, solution channels, and from recrystallization and dolomitization. Intergranular porosity occurs principally in unconsolidated sands and in sandstones, and can be measured reasonably well in the laboratory using core samples taken from wells. Porosity contributed by fractures and solution channels is difficult to measure in the laboratory. Various borehole geophysical methods that will be discussed later can be used to determine the porosity of strata in place. Porosity values in reservoir formations range from a maximum of about 0.40 in unconsolidated sands to as little as 0.02 in dense limestones. Porosity in the Mt. Simon Formation of Illinois ranges from about 0.20 to 0.02, as shown in Figure 16.

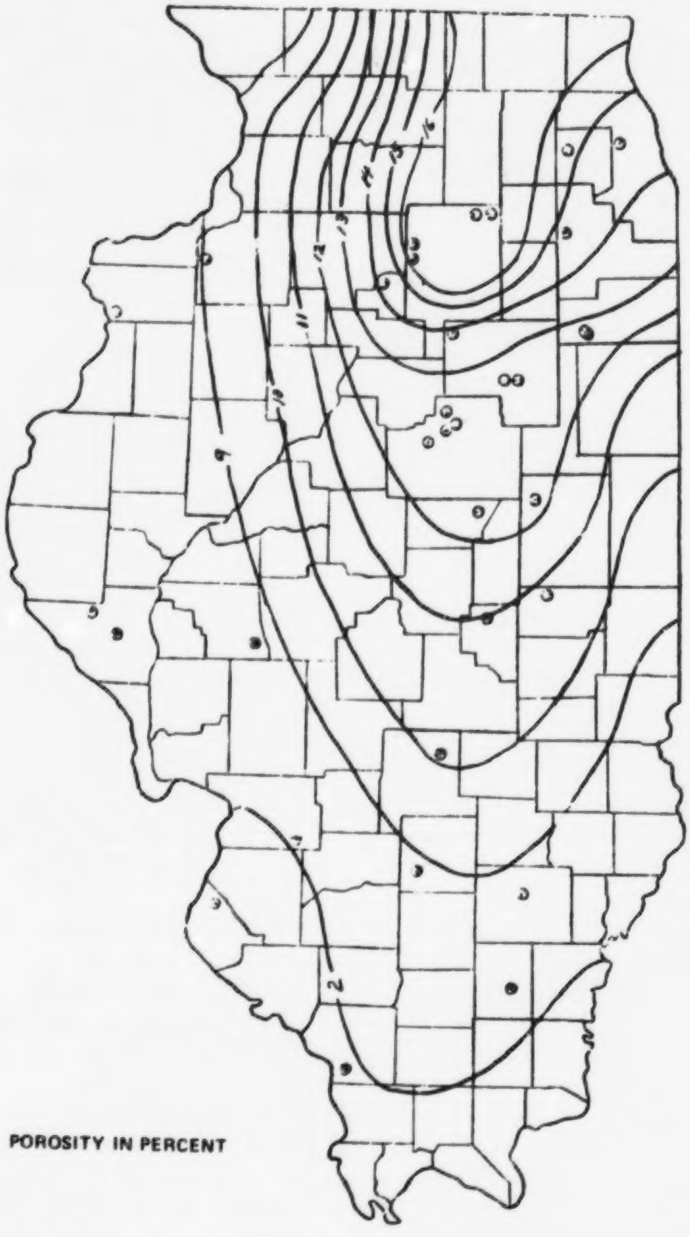
16
15
14
13
12
11
10
9
2
POROSITY IN PERCENT

Figure 16. Map showing distribution of the average porosity of the Mt. Simon Formation in Illinois.

Permeability

Permeability is the capacity of a rock to transmit fluid. Permeability is quantified by the coefficient of permeability or hydraulic conductivity. When both the properties of the fluid and the porous medium are considered, the coefficient of permeability $\overline{K}$ is defined by Darcy's law as:

$$\overline{K} = \frac{Q\mu}{A\rho g}\frac{dL}{dh} \quad (L^2) \tag{3}$$

where Q = flow rate through porous medium
A = cross-sectional area through which flow occurs
μ = fluid viscosity
ρ = fluid density
L = length of porous medium through which flow occurs
h = fluid head loss along L
g = acceleration of gravity.

The unit of permeability used in oil field work is the darcy. Substitution of $p = \rho gh$ into Equation 3 results in Equation 4:

$$\overline{K} = \frac{Q\mu}{A}\frac{dL}{dp} \quad (L^2) \tag{4}$$

From Equation 4, the darcy has been defined as

$$1 \text{ darcy} = \frac{1 \text{ cm}^3/\text{sec} \times 1 \text{ centipoise} \times 1 \text{ cm}}{1 \text{ cm}^2 \times 1 \text{ atmosphere}}$$

A still simpler form of Darcy's law is used in groundwater studies where the density and viscosity of water do not vary greatly:

$$K = \frac{Q}{A}\frac{dL}{dh} \quad (L/T) \quad . \tag{5}$$

The constant K is referred to as hydraulic conductivity and is usually expressed with the dimenstions cm/sec (L/T) or in U.S. Geological Survey units which are gallons/day × ft^2 (meinzers). A table for conversion of permeability units is given below (Table 3).

Permeability values for the formations used for wastewater injection range generally from several darcys to less than a millidarcy (one millidarcy = 10^{-3} darcy). Average permeability values for the Mt. Simon Formation in Illinois range from more than 100 millidarcys in the north to less than 1 millidarcy in the south. The permeability of shale beds

Table 3. Table of equivalency of permeability values in various units (Davis and Deweist, 1966, p. 165).

1 darcy	$= 9.87 \times 10^{-9}$ cm^{-2} $= 1.062 \times 10^{-11}$ ft^2
10^{-10} cm^2	$= 1.012 \times 10^{-12}$ darcys
0.1 cm/day	$= 1.15 \times 10^{-6}$ cm/sec $\approx 1.18 \times 10^{-11}$ cm^2 for water at 20°C
1.0 cm/sec	$\approx 1.02 \times 10^{-5}$ cm^2 for water at 20°C
1 darcy	$\approx$ 18.2 meinzer units for water at 60°F
1 meinzer	$=$ 0.134 ft/day $= 4.72 \times 10^{-5}$ cm/sec $\approx$ 5.5×10^{-2} darcys for water at 60°F

in the Eau Claire Formation, overlying the Mt. Simon Formation, is consistently less than 0.001 millidarcy.

A useful constant in hydrogeologic work is the coefficient of transmissivity (transmissibility) which is the permeability or hydraulic conductivity multiplied by the thickness of the aquifer. When the unit of permeability is the darcy, transmissivity is in darcy-feet/centipoise.

Compressibility

The compressibility of an aquifer includes the compressibility of the aquifer skeleton and that of the contained fluids. Thus, the total compressibility of an aquifer is

$$C = \phi\beta + \alpha \quad (F/L^2)^{-1} \tag{6}$$

where C = compressibility of aquifer (pressure^{-1})
ϕ = porosity
β = compressibility of water
α = compressibility of aquifer skeleton.

The compressibility of water has previously been discussed. The compressibility of aquifer skeletons varies greatly, from as little as 1×10^{-8} psi^{-1} in consolidated rocks to as much as 1×10^{-5} psi^{-1} in unconsolidated materials.

The coefficient used in analysis of reservoir response to injection or pumping is the storage coefficient (storativity), which is defined by:

$$S = \phi\gamma b\left(\beta + \frac{\alpha}{\phi}\right) \quad \text{(dimensionless)} \tag{7}$$

where ϕ, β, and α are as previously defined, and

S = storage coefficient
$\gamma = \rho g$ = specific weight of water per unit area
b = aquifer thickness.

The storage coefficient is the volume of water an aquifer releases or takes into storage per unit surface area per unit change in hydraulic head. The storage coefficient may be estimated from the equation above, or may be determined from aquifer tests that will be described later. Values of S are reported to range from 5×10^{-5} to 5×10^{-3} for confined aquifers. As an estimate of the value of S for the Mt. Simon Formation in northern Illinois assume that ϕ = 11 percent, b = 1,700 ft, γ = 0.45 psi/ft, $\beta = 3.0 \times 10^{-6}$ psi^{-1}, and* $\alpha = 6.7 \times 10^{-6}$. Then, from the equation above, $S \approx 5.4 \times 10^{-3}$. This is a high value, but the aquifer is very thick. If the compression of the water alone were considered, then S would be 2.5×10^{-4}. The Illinois State Water Survey (1973) estimated an average storage coefficient of 1×10^{-4} for the Mt. Simon Formation in northern Illinois, which is probably too low if the entire thickness of the formation is considered.

Temperature

The temperature of the aquifer and its contained fluids is important because of the effect that temperature has on fluid properties. The temperature of shallow groundwater is generally about 2° to 3° greater than the mean annual air temperature. In Illinois, this is from about 60°F in the south to 50°F in the north. Below 30 to 60 feet, the temperature increases approximately 1° to 2°F per 100 feet of depth. Figure 17 is a geothermal gradient map of Illinois and Indiana. At a depth of 3,000 feet, in northern Illinois, the calculated temperature would be about 86°F. The measured temperature at 3,000 feet near Pontiac, Illinois, was 90°F. Geothermal gradient maps for the United States have been prepared by the American Association of Petroleum Geologists (AAPG), Tulsa, Oklahoma, and can be obtained from that organization. Figure 17 is a modification of one of the AAPG maps.

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*Testing of the Mt. Simon Formation, in a gas storage field in northern Illinois, yielded a value of compressibility of the formation and its contained water of about 7×10^{-6}. Since the water only occupies 11 percent of the rock, the rock skeleton compressibility at that location is 6.7×10^{-6}.

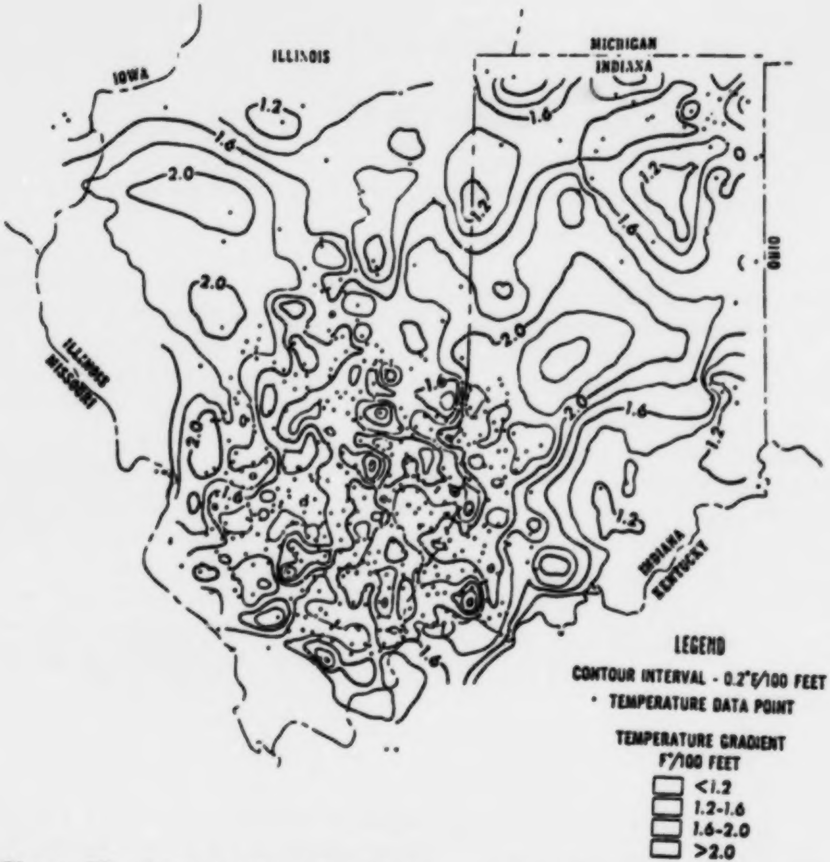

IOWA
ILLINOIS
MICHIGAN
INDIANA
OHIO
ILLINOIS
MISSOURI
INDIANA
KENTUCKY
1.2
1.6
2.0
LEGEND
CONTOUR INTERVAL - 0.2°F/100 FEET
• TEMPERATURE DATA POINT
TEMPERATURE GRADIENT
F°/100 FEET
☐ <1.2
☐ 1.2-1.6
☐ 1.6-2.0
☐ >2.0

Figure 17. Reproduction of portfolio map No. 10, American Association of Petroleum Geologists Geothermal Survey of North America (Gould, 1974).

State of Stress

In order to predict the pressure at which hydraulic fracturing or fault movement would be expected to occur, it is necessary to estimate the state of stress at the depth of the injection horizon. On the other hand, determination of the actual fracture pressure allows computation of the state of stress (Kehle, 1964).

The general equation for total normal stress across a plane in a porous medium is:

$$S_t = p_o + \sigma_i \quad (F/L^2) \tag{8}$$

where S_t = total stress
p_o = fluid pressure
σ_i = effective or intergranular normal stress.

Effective stress, as defined by Equation 8, is the stress available to resist hydraulic fracturing or the stress across a fault plane that acts to prevent movement on that fault. The equation shows that, if total stress remains constant, an increase in fluid pressure reduces the effective stress and a decrease in fluid pressure increases effective stress. When the effective stress is reduced to zero by fluid injection, hydraulic fracturing occurs. Fault movement will occur before normal stresses across the fault plane are reduced to zero, since there must be some shear stress acting on the fault blocks to cause them to move.

In a sedimentary rock sequence, the total normal vertical stress increases with depth of burial under increasing thicknesses of rock and fluid. It is commonly assumed, and the validity of the assumption can easily be verified, that the normal vertical stress increases at an average of about 1 psi/ft of depth. The lateral stresses may be greater or less than the vertical stress, depending on geologic conditions. In areas where crustal rocks are being actively compressed, lateral stresses may exceed vertical ones. In areas where crustal rocks are not in active compression, lateral stresses should be less than the vertical stress. The basis of estimating lateral stress prior to drilling of a well is hydraulic fracturing data from nearby wells and/or knowledge of the tectonic state of the region in which the well is located. The tectonic state of various regions is only now being determined. For example, Kehle (1964) concluded, as a result of hydraulic fracturing data from four wells, that the stresses at the well locations in Oklahoma and Texas were representative of an area that was tectonically in a relaxed state. In contrast, Sbar and Sykes (1973) characterized much of the eastern and north-central United States as being in a state of active tectonic compression. Further discussion concerning the state of stress and hydraulic fracturing will be presented in the section on hydraulic fracturing.

HYDRODYNAMICS

Hydrodynamics, as the term has been adopted for use in subsurface hydrology, refers to the state of potential for flow of subsurface fluids, particularly in deep sedimentary basins. As examples of its application recent publications by Bond (1972) and Clifford (1973) discuss the flow potential in deep aquifers of Illinois, Indiana, and Ohio as determined from pressure, water level, and water density measurements made in deep wells.

The potential for flow in deep aquifers that are used for wastewater injection is important, because it can be used to estimate natural groundwater flow rates and directions. Figure 18 is a map showing the potentiometric surface of the Mt. Simon Formation Formation in Ohio and Indiana. The arrows indicate the directions of regional groundwater flow in the Mt. Simon Formation as indicated by the potentiometric contours. Bond (1972 and 1973) discusses some of the difficulties in interpretation and application of potentiometric data.

RESOURCES

An objective in the monitoring of subsurface wastewater injection is to verify that fresh groundwater, oil or gas, coal, or other subsurface resources are not being jeopardized. Therefore, the occurrence and distribution of all significant subsurface resources must be determined. This determination is made by reference to published reports and by consultation with public officials, companies, and individuals familiar with subsurface resources of the area. Also, the actual drilling of the well will show the location and nature of resources present at depth at the well site.

In reviewing the occurrence of subsurface resources, the locations, construction, use, and ownership of all wells, both shallow and deep within the area of influence of the injection well should be determined. The plugging record for all abandoned deep wells should be obtained to

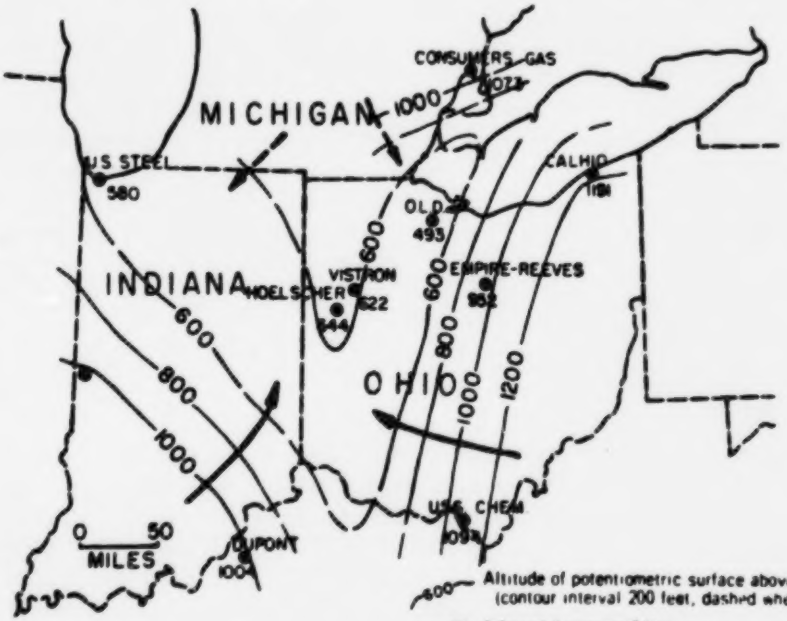

MICHIGAN
INDIANA
OHIO
CONSUMERS GAS
1077
1000
US STEEL
580
CALHIO
1181
OLD
493
VISTRON
622
HOELSCHER
644
EMPIRE-REEVES
952
600
800
1000
1200
U.S.S. CHEM
1093
DUPONT
100
0
50
MILES
600
Altitude of potentiometric surface above sea level (contour interval 200 feet, dashed where inferred)
Inferred direction of flow

Figure 18. Potentiometric surface of the Mt. Simon Formation in Ohio and vicinity (Clifford, 1973).

verify the adequacy of such plugging. In States where oil has been produced for many years there are often areas where wells are known to have been drilled, but for which no records are available, and there are also wells which are located but for which plugging records are not available or for which plugging is known to have been inadequate. Document-ing the status of deep wells near the injection well may be the most important step in monitoring of injection wells in areas that are or have been active oil or gas provinces, because these wells provide the greatest hazard for escape of wastewater or formation water from otherwise well-confined aquifers.

SECTION V

ACQUISITION OF SUBSURFACE DATA

PRIOR TO DRILLING

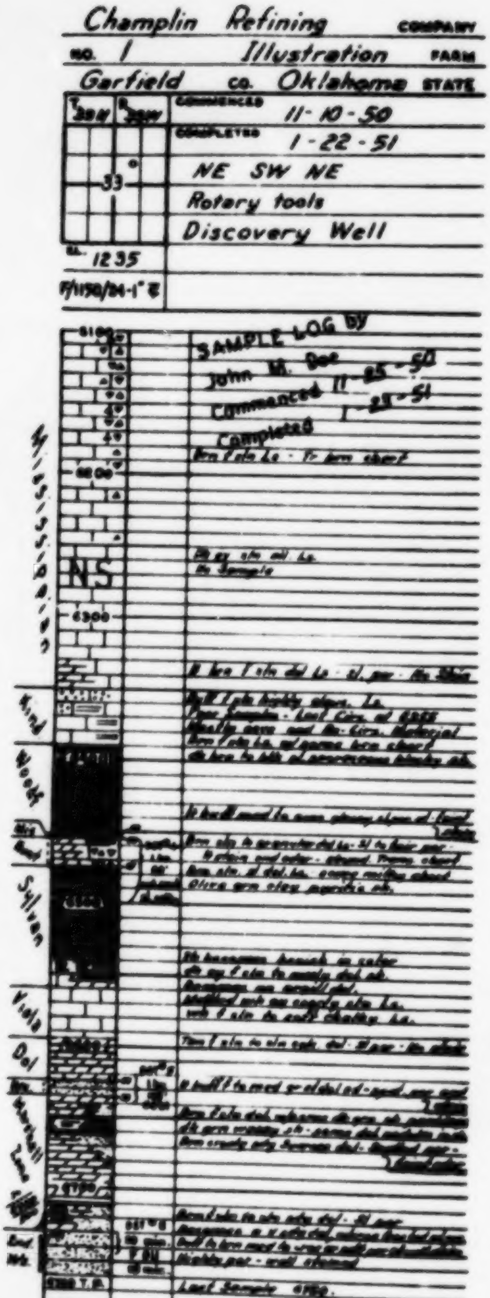
In order to estimate the performance of injection wells and to evaluate the subsurface environment prior to construction, the types of information described in Section IV, The Subsurface Environment, are estimated from sources such as the figures and tables from that section. The information in those figures and tables has, of course, come from previously drilled wells; and if it has not been compiled on maps, cross sections, and tables, then this may be necessary before it can be used. Basic information for previously drilled wells is available in most States through State geological surveys, oil and gas agencies and water resources agencies. In addition, private companies acquire and sell well logs, and other subsurface data. In some cases it may be necessary to go to individual oil companies or consultants for subsurface data that are not publically available. Companies and individuals are usually cooperative in releasing information that is not considered confidential.

DURING WELL CONSTRUCTION AND TESTING

Rock Samples

Most deep wells drilled today are drilled by rotary drilling rigs. Rotary drilling rigs use two basic types of drilling bits, rock bits and core bits. Rock bits grind the strata into small chips that are usually carried from the hole by a viscous drilling mud, but sometimes by water or air. The chips are periodically collected, usually after each 5 or 10 feet of new hole, washed, and examined with a low-powered binocular microscope. The methods for collection, examination, and description of such samples are presented in a reference edited by Haun and LeRoy (1958). Figure 19 is an example of a sample log prepared by examination of cuttings. Soft, unconsolidated clays will not yield chips, but will break down into mud and unconsolidated or soft sandstones into individual grains when drilled. Samples are of only limited value in such areas.

Cores taken with rotary core bits and barrels give a much more accurate picture of the subsurface formations than cuttings, but core samples are very expensive (>$50/ft) in deep wells and can usually only be afforded in limited numbers. In deep wells, core samples are commonly about


Champlin Refining COMPANY
NO. 1 Illustration FARM
Garfield CO. Oklahoma STATE
COMMENCED 11-10-50
COMPLETED 1-22-51
33
NE SW NE
Rotary tools
Discovery Well
EL. 1235
SAMPLE LOG BY
John M. Doe
Commenced 11-25-50
Completed 1-25-51
6100
6200
6300
NS
Mississippian
Kind
Woodf
Sylvan
Viola
Dol
T.D.
Last Sample

LEGEND

▤	Limestone
▤	Ls. w/chert
▤	Ls. w/glauc.
▤	Dolomite
■	Shale
▨	Sand
NS	No Sample
|	Oil Stain

Figure 19. Sample log (Moore, 1951).

four inches in diameter. Cores are described just as are cuttings, but since a continuous sample of the formation is available, a detailed foot by foot description can be prepared (Table 1). Whole-core samples can be analyzed for porosity and permeability in the laboratory, or small cores can be taken from the large core and analyzed. The latter procedure is the most common. Table 4 shows typical laboratory core data from the Mt. Simon Formation in Illinois.

Table 4. Laboratory core analysis data from the Mt. Simon Formation in Illinois.[a]

Sample Number	Depth (feet)	Permeability (millidarcys) Horizontal	Permeability (millidarcys) Vertical	Porosity (percent)
408	3154.5	6.9	0.11	6.4
409	3155.5	<0.10	0.17	6.4
410	3156.6	<0.10	<0.10	9.7
411	3157.5	0.17	0.31	8.6
412	3158.5	0.26	0.72	8.3
413	3159.5	<0.10	<0.10	8.1
414	3160.5	1.9	0.12	9.6
415	3161.5	<0.10	<0.10	8.7
416	3162.5	2.3	0.98	8.1
417	3163.5	0.43	0.46	6.2
418	3164.5	12.	0.12	8.2
419	3165.5	3.1	1.1	14.7
420	3166.5	0.31	0.44	10.7
421	3167.5	7.8	0.79	10.0
422	3168.5	8.5	5.4	9.9
423	3169.5	5.0	3.2	7.2
424	3170.5	6.2	3.6	6.9
425	3171.5	3.4	1.2	8.3
426	3172.5	10.	2.5	12.2
427	3173.5	1.4	0.46	8.9
428	3174.5	11.	2.0	8.0
429	3175.5	8.5	1.5	8.2
430	3176.5	2.6	0.91	7.7
431	3177.5	0.74	<0.10	5.9

Note:

[a] Mt. Simon Core No. 15 3148.0 - 3178.0

Formation Fluids

Samples of water from subsurface formations can be obtained from deep wells before they are completed, from cores, by formation testing devices, and by swabbing.

When cores are taken, as previously described, the water in the cores can be carefully extracted and its chemistry analyzed. Contamination is a serious problem, since the core has been exposed to infiltration by drilling mud and mud filtrate.

Drill-stem testing is a technique whereby a zone in an open borehole can be isolated by an expandable packer or packers and fluid from the formation allowed to flow through a valve into the drill pipe.

The basic drill-stem test tool assembly consists of:

1. A rubber packing element or packer which can be expanded against the hole to segregate the annular sections above and below the element
2. A tester valve to (a) control flow into the drill pipe, that is, to exclude mud during entry into the hole and to allow formation fluids to enter during the test, and an equalizing or bypass valve to (b) allow pressure equalization across the packer(s) after completion of the flow test.

Figure 20 illustrates the procedure for testing the bottom section of a hole. While going in the hole, the packer is collapsed, allowing the displaced mud to rise as shown by the arrows. After the pipe reaches bottom and the necessary surface preparations have been made, the packer is set (compressed and expanded); this isolates the lower zone from the rest of the open hole. The compressive load is furnished by a slacking off of the desired amount of drill-string weight, which is transferred to the anchor pipe below the packer.

The tester valve is then opened and thus the isolated section is exposed to the low pressure inside the empty, or nearly empty, drill pipe. Formation fluids can then enter the pipe, as shown in the second picture. At the end of the test, the tester valve is closed, trapping any fluid above it, and the bypass valve is opened to equalize the pressure across the packer. Finally, the setting weight is taken off and the packer is pulled free. The pipe is then pulled from the hole until the fluid-containing section reaches the surface. As each successive pipe section is removed, its fluid content may be examined.

Although the above is a very common type of test, there are many other variations of procedure, as indicated in Figure 21. The straddle packer

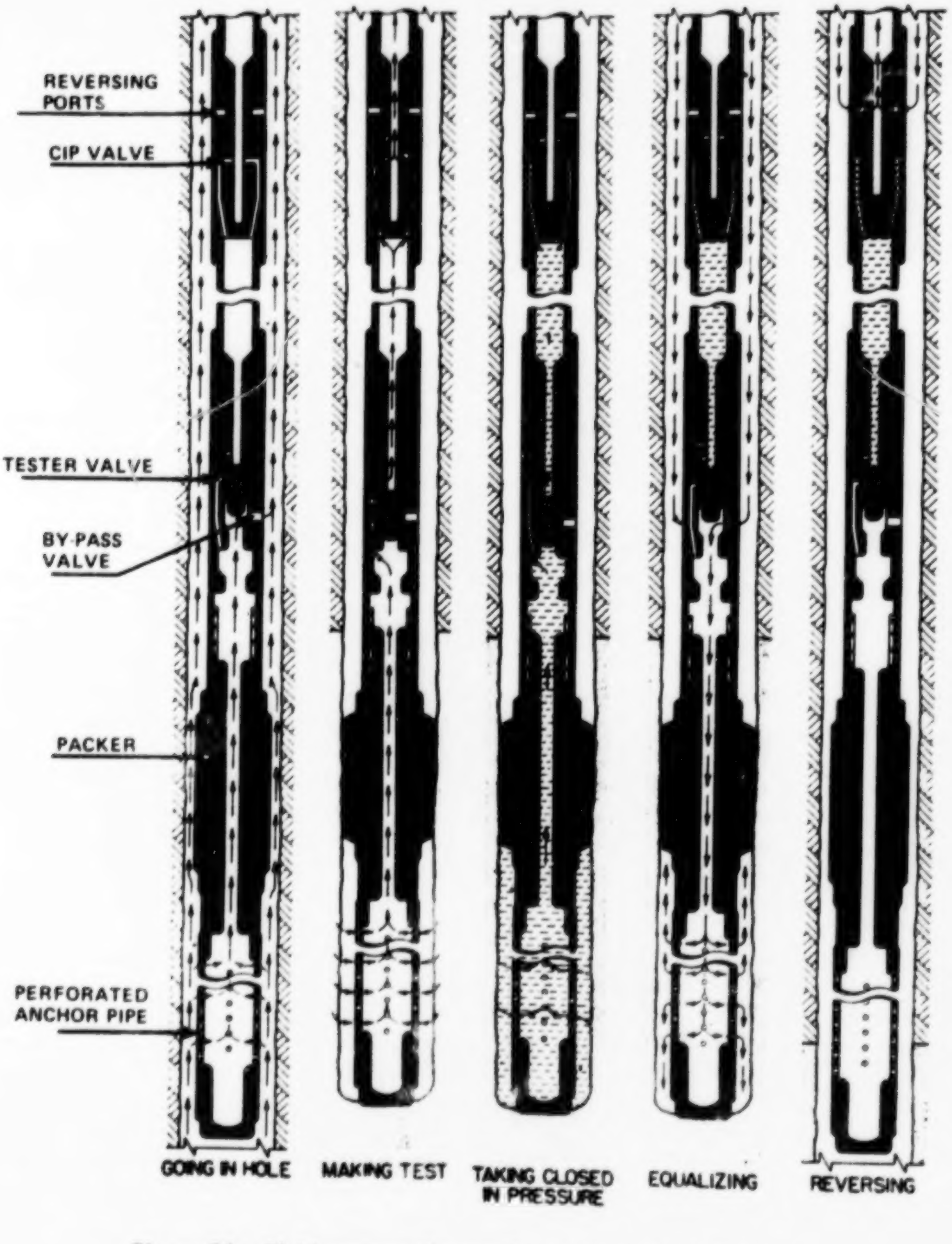

REVERSING PORTS
CIP VALVE
TESTER VALVE
BY-PASS VALVE
PACKER
PERFORATED ANCHOR PIPE
GOING IN HOLE
MAKING TEST
TAKING CLOSED IN PRESSURE
EQUALIZING
REVERSING

Figure 20. Fluid passage diagram for a conventional bottom section, drill stem test (Gatlin, 1960).

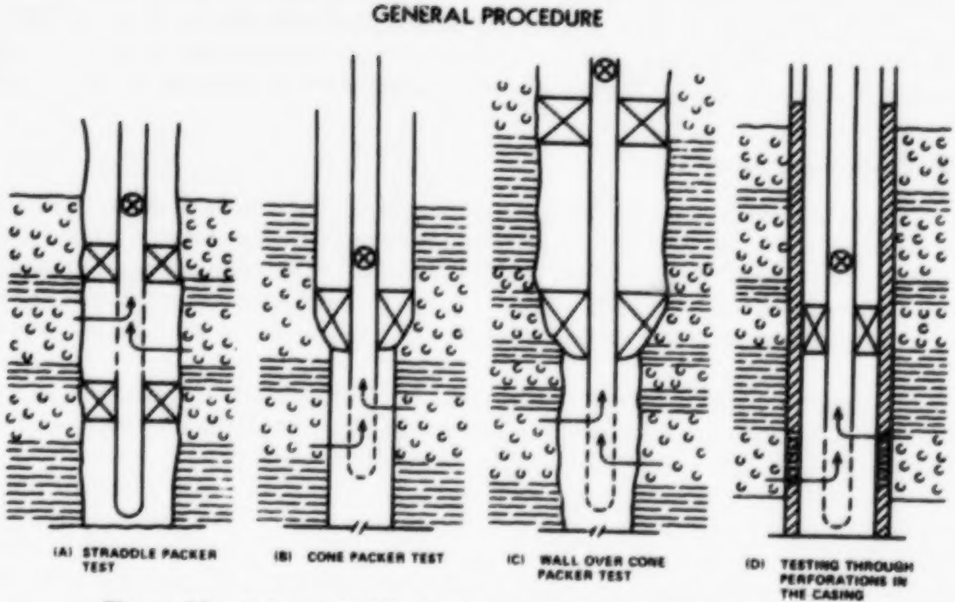

GENERAL PROCEDURE
(A) STRADDLE PACKER TEST
(B) CONE PACKER TEST
(C) WALL OVER CONE PACKER TEST
(D) TESTING THROUGH PERFORATIONS IN THE CASING

Figure 21. Schematic illustration of various drill stem test conditions (Kirkpatrick, 1954).

test is necessary when isolation from formations both above and below the test zone is necessary. Such a situation commonly arises when it is desired to test a zone previously passed by. Straddle testing is less desirable than conventional testing, from both a cost and an operational hazard standpoint. Two packers are more apt to become stuck than one, since any material which sloughs or caves from the test zone may accumulate between the packers. Also, two positive, pressure-tight packer-formation seals are required for a successful test. Consequently this procedure is not preferred, and is applied only when necessary. This should not be construed to mean that these disadvantages prevent one from making such tests but rather that the additional problems the tests entail should be recognized.

Formation testing devices are available which can be lowered into the borehole on a wire line. In this case, the sample is limited to the amount that can be contained in the testing device (up to about 5 gallons).

Swabbing is a method of producing fluid that is similar to pumping a well. In swabbing, fluid is lifted from the borehole through drill pipe, casing, or tubing by a swab that falls freely downward through the pipe and its contained fluid, but which seats against the pipe walls on the upstroke, drawing a volume of fluid above it as it is raised. Swabbing may be used in conjunction with drill-stem testing to increase the volume of fluid obtained. The advantage of swabbing is that it can be continued until all drilling mud has been drawn from the pipe and the formation and the chemistry of the water obtained reaches a steady state. This procedure helps to insure that a representative sample of formation water is obtained.

Borehole Geophysical Logs

After a well has been drilled, a variety of borehole logging tools are available that can be used to produce a record of the nature of the formations penetrated and their contained fluids. In borehole logging, a probe is lowered into a well at the end of a wire cable and selected geophysical properties are measured and recorded at the surface as a function of depth.

Current methods of well logging are too numerous to discuss in detail here. A broad classification of the more commonly used methods is shown in Table 5, together with their main applications. Because the variety of available logging methods is so great, the suite used in logging a well must be carefully selected to provide the desired information at an acceptable cost. Local practice in the particular geographic area is a valuable guide, since it represents the cumulative experience obtained from logging many wells. Some of the objectives in logging injection wells will generally be: determination of lithology; bed thickness; amount, location and type of porosity; and salinity of formation water. In order to achieve these objectives, a commonly chosen suite of logs will include a gamma ray log, a focused resistivity log, and one or more porosity measuring logs selected from among the various radiation and elastic wave logs. Some other frequently used logs include the spontaneous potential (SP) and nonfocused electric logs, the caliper log and the temperature log.

Figures 22, 23, and 24 are intervals from a Laterlog-gamma ray-neutron* log, a sonic log, and a temperature-caliper log run in a waste-water disposal well in northern Illinois. On the Laterlog-gamma ray-neutron log, the contact between the Eau Claire Formation and the Mt. Simon Formation is shown at 3108 feet where it was picked by the Illinois Geological Survey. However, it is apparent from the gamma ray log that, for engineering purposes, the shale confining interval terminates at 2900 feet and that sandstones usable for injection begin at 2900 feet. From the sonic log, it can be seen that the first sandstone interval from 2900 to 2940 feet has an average interval transit time of about 72 microseconds per foot. Using tables provided by the logging company (Schlumberger, 1972a) and a matrix velocity of 19,500 ft/second, the average porosity of this sandstone body is estimated as 15 percent. The temperature log shows a temperature of about 83.5°F from 2900 to 2940 feet, and from

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*"Laterlog" is a trade name of Schlumberger Ltd., for a resistivity log.

Table 5. Well logging methods and their applications (modified after Jennings and Timur, 1973).

Method		Property	Application
ELECTRICAL	Spontaneous Potential (SP)	Electrochemical and electrokinetic potentials	Formation water resistivity (R_w); shales and nonshales; bed thickness; shaliness
	Nonfocused Electric Log	Resistivity	a. Water and gas/oil saturation b. Porosity of water zones c. R_w in zones of known porosity d. True resistivity of formation (R_t) e. Resistivity of invaded zone
	Focused Conductivity Log	Resistivity	a, b, c, d Very good for estimating R_t in either freshwater or oil base mud
	Focused Resistivity Logs	Resistivity	a, b, c, d Especially good for determining R_t of thin beds Depth of invasion
	Focused and Nonfocused Microresistivity Logs	Resistivity	Resistivity of the flushed zone (R_{xo}) for calculating porosity Bed thickness
ELASTIC WAVE PROPAGATION	Transmission	Compressional and shear wave velocities	Porosity; lithology; elastic properties, bulk and pore compressibilities
		Compressional and wave attenuations	Location of fractures; cement bond quality
	Reflection	Amplitude of reflected waves	Location of vugs, fractures; orientation of fractures and bed boundaries; casing inspection

(continued)

Table 5 — Continued

Method		Property	Application
RADIATION	Gamma Ray	Natural radioactivity	Shales and nonshales; shaliness
	Spectral Gamma Ray	Natural radioactivity	Lithologic identification
	Gamma-Gamma	Bulk density	Porosity, lithology
	Neutron-Gamma	Hydrogen content	Porosity
	Neutron-Thermal Neutron	Hydrogen content	Porosity; gas from liquid
	Neutron-Epithermal Neutron	Hydrogen content	Porosity; gas from liquid
	Pulsed Neutron Capture	Decay rate of thermal neutrons	Water and gas/oil saturations; reevaluation of old wells
	Spectral Neutron	Induced gamma ray spectra	Location of hydrocarbons; lithology
OTHER	Caliper	Borehole diameter	Calculation of cement volume; location of mud cake
	Dipmeter	Azimuth and inclination of bedding planes	Dip and strike of beds
	Deviation Log	Azimuth and inclination of borehole	Borehole position
	Gravity Meter	Density	Formation density
	Ultra-Long Spaced Electric Log	Resistivity	Salt flank location
	Nuclear Magnetism	Amount of free hydrogen; relaxation rate of hydrogen	Effective porosity and permeability of sands; porosity for carbonates
	Production or Injectivity	Temperature, flow rate, fluid specific gravity, pressure	Downhole production or injection
	Temperature Log	Temperature	Formation temperature

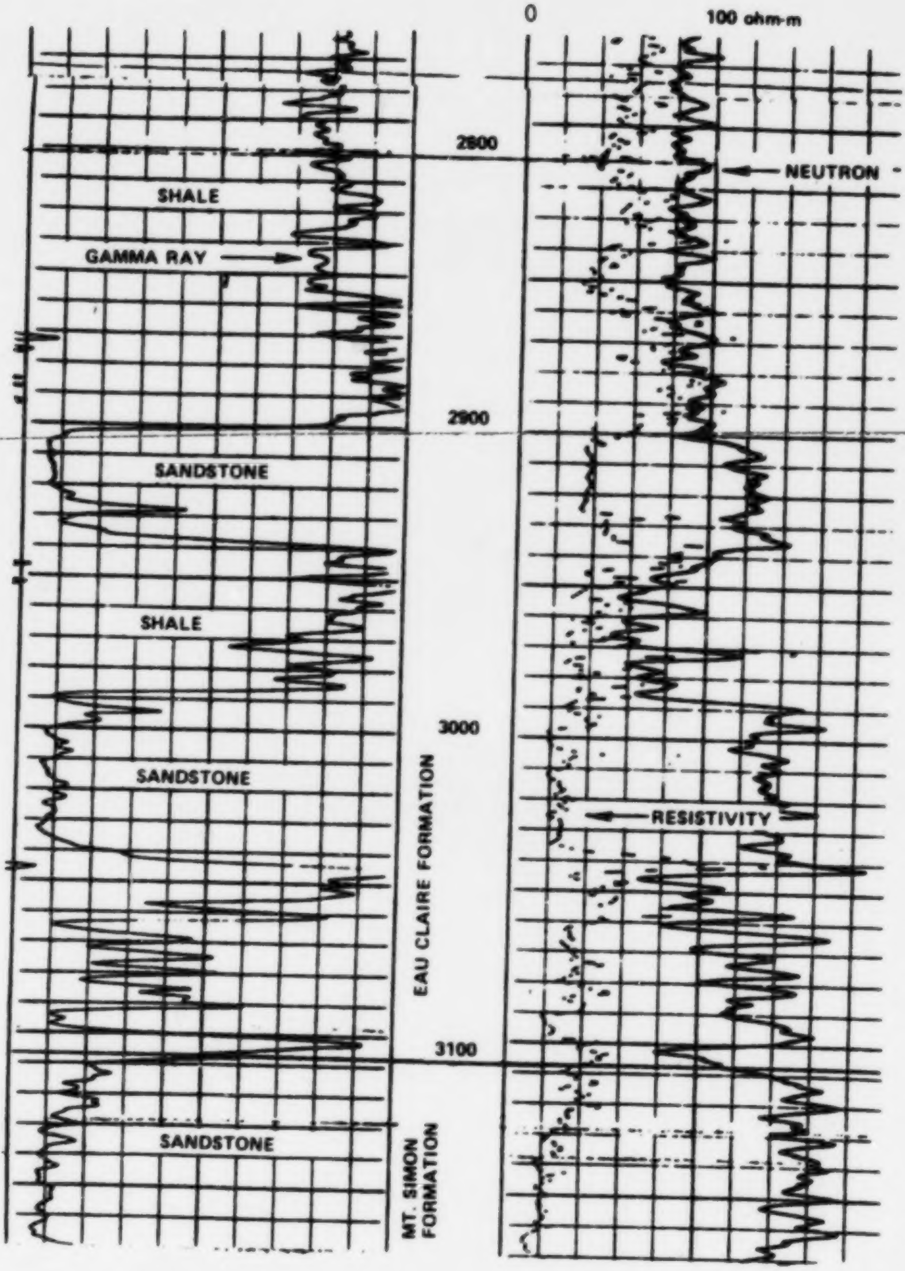


Figure 22. Portion of a Laterlog–gamma ray–neutron log from a deep well in northern Illinois.

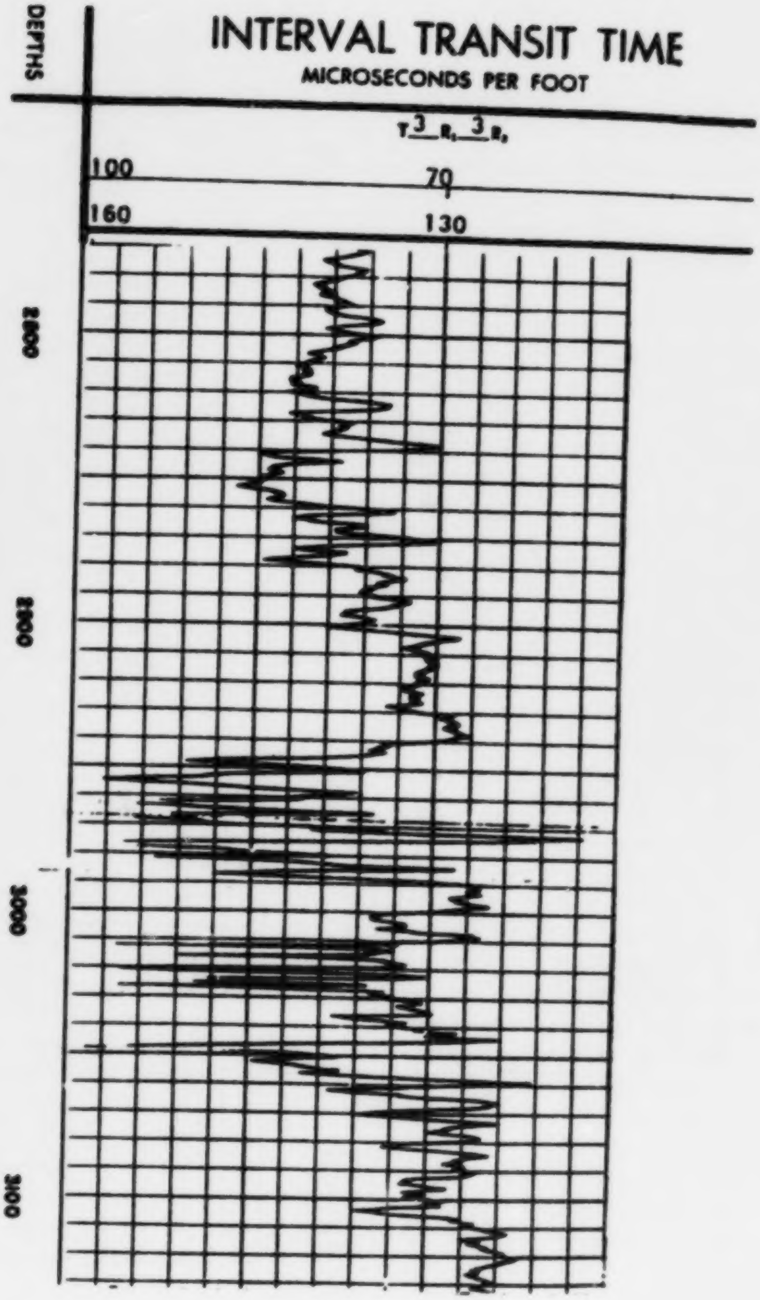


Figure 23. Portion of a sonic log from a deep well in northern Illinois.

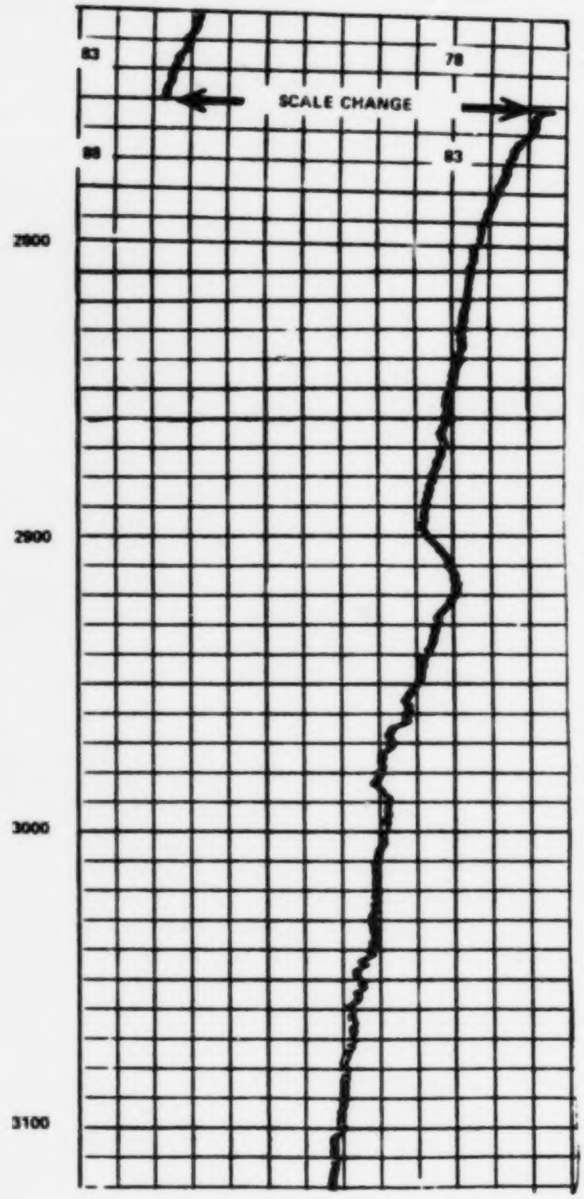


Figure 24. Portion of a temperature log from a deep well in northern Illinois.

the Laterlog (Figure 22), the resistivity of this interval is about 40 ohm-meters. From the Archie equation (Schlumberger, 1972) the formation factor F is 45 and the resistivity of the formation water is 0.625 ohm-meters. A sodium chloride water with a resistivity of 0.625 ohm-meters has a dissolved solids content of about 8,000 ppm at 83.5°F, Actually, the formation water salinity is probably about twice the calculated value because the Laterlog yields incorrectly high resistivities when run in low-salinity mud, as is the case here. An induction log would yield more accurate results in such a situation. This example illustrates some of the principal uses of borehole geophysical logs in conjunction with the evaluation of geological conditions in wastewater injection wells. Further uses will be covered in Section VII, on well monitoring. Keys and Brown (1973) give a more complete discussion of the application of borehole geophysical logs to wastewater injection than is possible here.

Testing of Injection Units and Confining Beds

Examination of the records of many of the wastewater injection wells that have been constructed up to the present time shows that, with few exceptions, the maximum amount of usable geologic and engineering information has not been obtained during the testing of wastewater injection wells. This is regrettable, because such tests provide the best basis for analyzing reservoir conditions prior to injection, for predicting the long-term behavior of the well and the reservoir, for detecting and understanding changes in well performance that may occur during operation, and for analyzing the history of a well from its records.

The methods for testing of pumping or injection wells and the techniques for analysis of test data are discussed in numerous textbooks and in hundreds of other publications concerning groundwater and petroleum engineering. Because the number of published articles and the scope of their content are so extensive, only a few selected references are mentioned and a few examples discussed here to establish the reasons for and methods of well testing.

A well can be tested by pumping from it or injecting into it. Measurements of reservoir pressure or water level can be made during pumping or injection or, alternatively, after pumping or injection has ceased and the reservoir is adjusting to its original condition. Furthermore, reservoir pressure or water level can be measured in the principal well or in adjacent observation wells. Any one of these approaches will yield much of the same information.

Drill Stem Testing

In the case of the usual deep and rather expensive wastewater injection well, there will be no observation well and testing will be in the well itself. In the sequence of well construction and testing, the first type of formation test that is likely to be made is the drill-stem test (DST). As has previously been mentioned, this test is analogous to a pumping test of limited duration. Quantitative analysis is usually made using data obtained during the period of pressure buildup following the period in which the reservoir is allowed to flow.

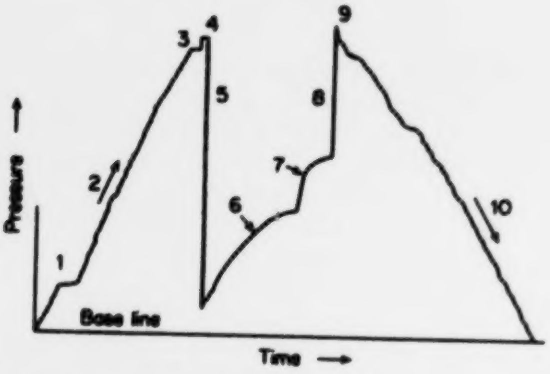
Figure 25a is a schematic DST pressure record, with a description of the sequence of events in a successful test. Figure 25b is a schematic representation of a test in which no fluid was produced. Conditions that may be encountered in a DST are widely variable and considerable experience may be required in order to interpret an unusual test. The companies that provide the testing services also provide assistance in test interpretation.

If a test is successful, pressure buildup data from the test are taken from the DST chart and tabulated. These data are then plotted as shown in Figure 26. A series of calculations of formation properties are then made. The properties that are routinely calculated and are of importance here are:

1. Static bottom-hole pressure
2. Transmissivity
3. Average effective permeability
4. Damage ratio
5. Approximate radius of investigation.

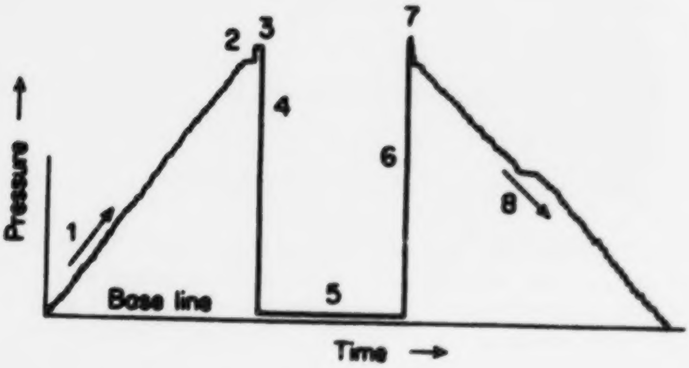
The static bottom-hole pressure as determined from a successful test is assumed to closely represent the formation pressure at the elevation of the pressure recording device. Transmissivity is average permeability multiplied by the thickness of the test interval. The damage ratio is an indication of the amount of plugging of pores in the formation during drilling of the well. In addition to this routine information, drill-stem tests may indicate the presence of and distance to nearby faults or facies changes that act as barriers to flow or channels for rapid flow.

For detailed presentations of drill-stem test analysis, the reader is referred to Gatlin (1960), Lynch (1962), Matthews and Russell (1967) and Pirson (1963). Also, literature such as that by Murphy (undated) is readily available from companies that provide drill-stem testing services.



1. Putting water cushion in drill pipe
2. Running in hole
3. Hydrostatic pressure (weight of mud column)
4. Squeeze created by setting packer
5. Opened tester, releasing pressure below packer
6. Flow period, test zone producing into drill pipe
7. Shut in pressure, tester closed immediately above packer
8. Equalizing hydrostatic pressure below packer
9. Released packer
10. Pulling out of hole

Figure 25a. Normal sequence of events as recorded on the chart during a successful drill-stem test (Kirkpatrick, 1954).



1. Running in hole
2. Hydrostatic pressure (weight of mud column)
3. Squeeze created by setting packer
4. Opened tester, releasing pressure below packer
5. Flow period, test zone open to atmosphere
6. Closed tester and equalizing hyd. pressure below packer
7. Pulled packer loose
8. Pulling out of hole

Figure 25b. Sequence of events as recorded during a drill-stem test when no fluids were produced (Kirkpatrick, 1954).

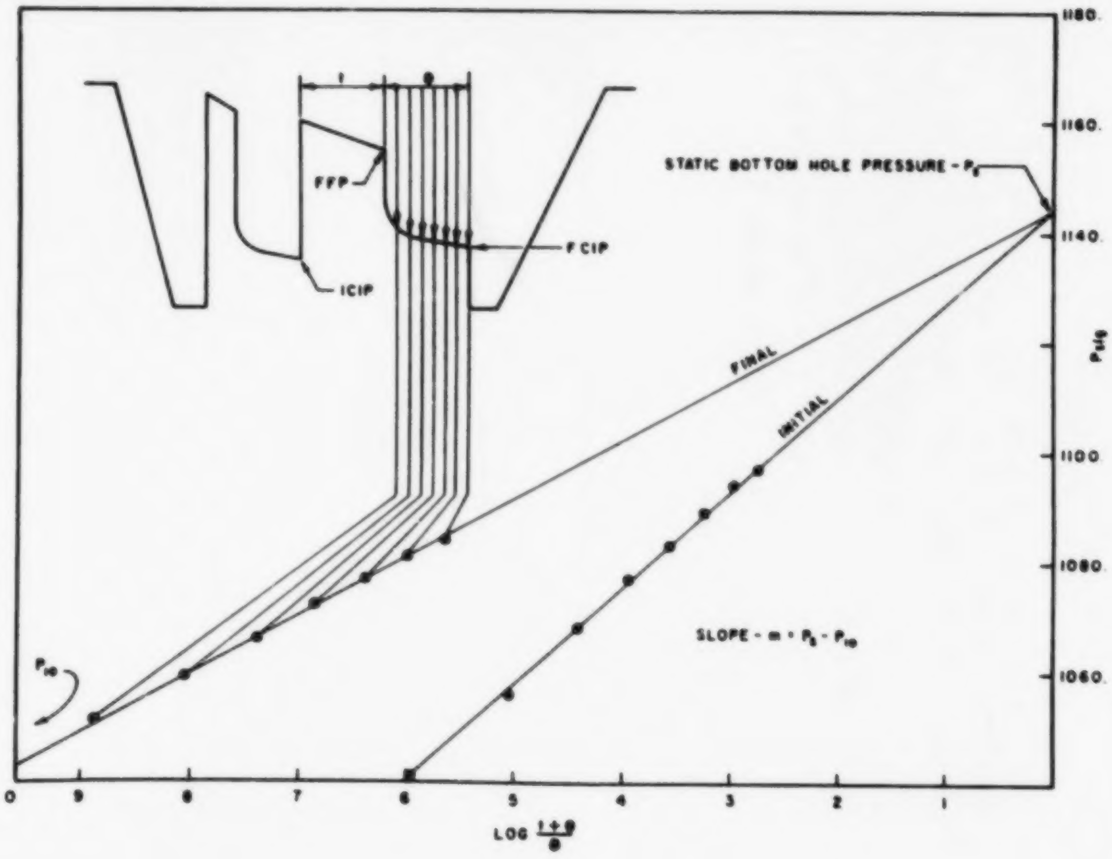


Figure 26. Example of a plot of data from a drill-stem test with dual closed-in periods (Murphy, undated).

As an example of DST analysis, data from testing of the Mt. Simon Formation in a well in Ohio were selected. Figure 27 is a plot of the pressure buildup data for that test. Extrapolation of the data to the logarithm of $(t + \theta)/\theta = 0$ shows that the static formation pressure is 2750 psig. The gage was at a depth of 5886 feet in the well, so the fluid pressure gradient is 0.467 psi per foot of depth.

For the remaining calculations, the following values from the test are needed (dimensionalized in oil field units):

P_f = final flow pressure = 1061 psig

t = final flow time = 62 min

$m = p_s - p_{10}$ = 163 psi per log cycle

Q = average flow rate = 347 bbls/day

μ = water viscosity = 1.065 centipoise

b = formation thickness = 105 ft.

Then,

$$T = \text{transmissivity} = 162.6 \frac{Q}{m} \quad \text{(millidarcy-ft/centipoise)} \qquad (9)$$

$$\overline{K} = \text{average permeability} = \frac{T\mu}{b} \quad \text{(millidarcys)} \qquad (10)$$

$$DR = \text{damage ratio} = \frac{0.183(p_s - p_f)}{m} \quad \text{(dimensionless)} \qquad (11)$$

$$r = \text{radius of investigation} \cong (\overline{K}t)^{1/2} \quad . \qquad (12)$$

The transmissivity is computed to be 345 millidarcy-ft/centipoise, the average permeability 3.5 millidarcys, the damage ratio 1.9, and the radius of investigation 14.73 ft. These calculations reveal that the Mt. Simon Formation at this location has a very low capacity to accept injected fluids. The capacity could theoretically be improved nearly 100 percent by removing formation damage; reservoir stimulation by hydraulic fracturing would also help, but the reservoir is not promising. No hydrologic boundaries were encountered within the radius of investigation, which was only about 14 feet. Further well testing and core analysis results to confirm these findings are discussed in the material that follows.

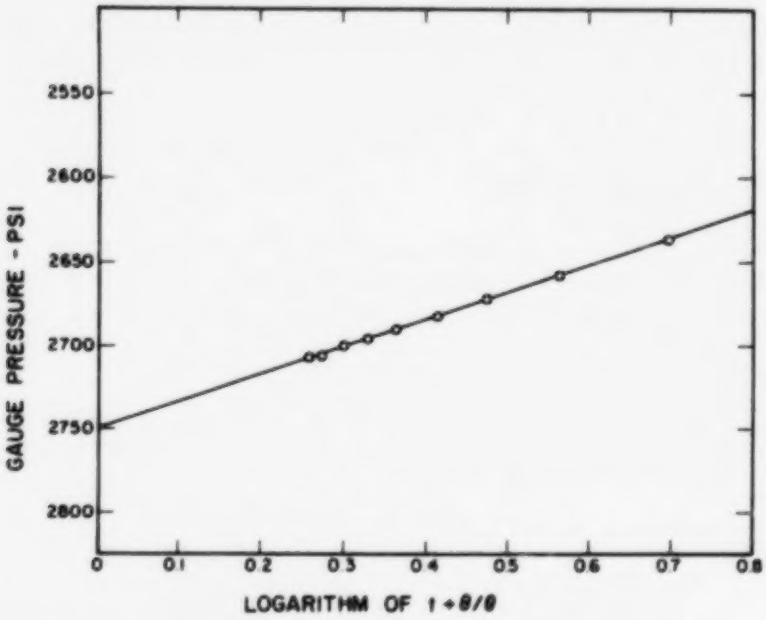


Figure 27. Plot of extrapolated pressure from drill-stem test data from an injection well in Ohio.

Injectivity Tests

After an injection well has been drilled and possible injection intervals identified by coring, by geophysical logging, and by drill-stem testing, injection tests will usually be run. For initial injection testing, truck-mounted pumps are often rented and treated water used for injection rather than wastewater. Frequently, more than one possible injection interval is present and tests are performed on the intervals individually or on more than one at a time. The common practice when performing an injection test is to begin injection at a fraction of the final estimated rate, to inject at this rate for at least several hours, then to repeat this process at increasingly greater rates until a limiting rate or pressure is reached. Injection is then stopped and the reservoir allowed to return to its original pressure state. Pressures may or may not be recorded during this fall-off period.

Regardless of the sequence in which a test is performed, if pressure, time, and flow data are accurately recorded, and the test is run long enough, it is theoretically possible to analyze the test. However, the simpler the test the simpler and probably more reliable the interpretation. Tests performed on more than one interval at a time are particularly difficult to interpret and should be avoided if possible or, alternatively, both single and multiple zone tests performed.

Figure 28 is a plot of the data from a constant-rate injectivity test of the Mt. Simon Formation. The test was run at 75 gpm for about 25 hours. The equation used to determine formation transmissivity from Figure 28 is:

$$T = \frac{2.30Q}{4\pi\ \Delta h} \quad (L^2/T) \quad . \tag{13}$$

Alternatively, Equation 9 can be used. Any consistent units can be used in Equation 13, whereas Equation 9 is dimensionalized for oil field units as previously indicated.

Using Equation 9

$$T = \frac{162.6 \times 2571 \text{ bbl/day}}{925 \text{ psi/log cycle}} = 452 \text{ millidarcy-ft/centipoise} \quad .$$

Using Equation 13

$$T = \frac{2.30 \times 14,434 \text{ ft}^3\text{/day}}{4\pi \times 2136 \text{ ft/log cycle}} = 1.24 \text{ ft}^2\text{/day}$$

or $$T = 9.3 \text{ gal/day} \cdot \text{ft} \quad .$$

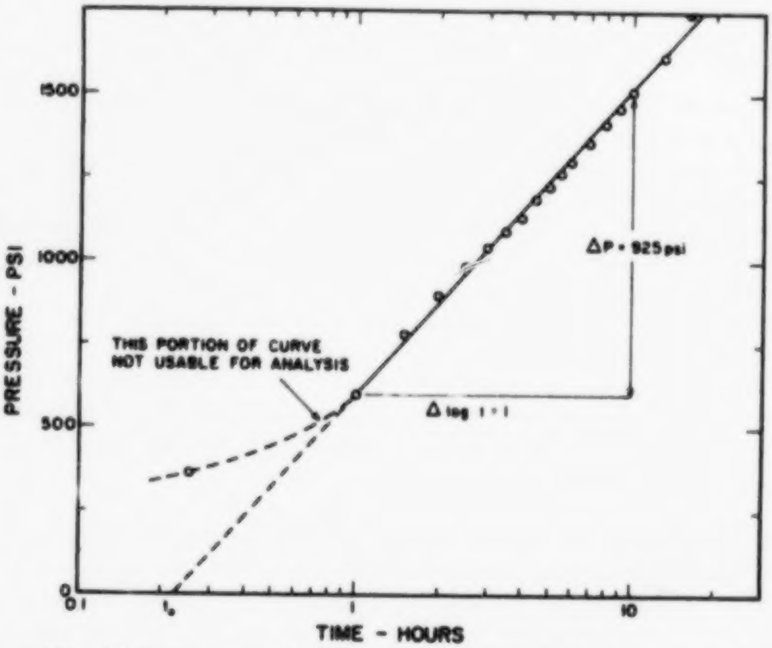


Figure 28. Plot of pressure buildup data from an injectivity test of the Mt. Simon Formation in Ohio.

This test was run on the same well for which the drill-stem test analysis was given, but the well bore was cleaned up and acidized before the injectivity test, thus leading to a slightly higher transmissivity.

The injectivity test can further be used to determine the formation storage coefficient from

$$S = \frac{2.25\ Tt_o}{r^2} \quad \text{(dimensionless)} \tag{14}$$

where t_o = intercept of extrapolated test curve with time axis
r = radius of well bore.

In Figure 28, t_o = 2.2 hours and

$$S = \frac{2.25 \times 1.24\ \text{ft}^2/\text{day} \times 0.0092\ \text{days}}{(0.396)^2} = 0.16 \quad .$$

As was previously discussed, storage coefficient values for confined aquifers are generally at least three orders of magnitude lower than the calculated value of 0.16. As a better estimate, Equation 7 (page 27) yields a value for the storage coefficient of 3.34×10^{-4}. It is believed that the discrepancy in this case results from the fact that the well was hydraulically fractured during an earlier injection test, leading to a greatly enlarged effective well bore. As an estimate of the degree of enlargement, Equation 14 is rearranged and solved for r, using the calculated storage coefficient, yielding:

$$r = \sqrt{\frac{2.25\ Tt_o}{S}}$$

$$r = \sqrt{\frac{2.25 \times 1.24\ \text{ft}^2/\text{day} \times 0.009\ \text{days}}{3.34 \times 10^{-4}}} = 8.7\ \text{ft} \quad .$$

This is a reasonable value and will be used in later calculations.

If early time data are available, an alternative form of analysis that involves curve matching can be employed. Figure 29 is such a plot of recovery data for an injection well at Mulberry, Florida. The details of the analysis of this test are given by Wilson et al. (1973). The most interesting aspect of this example is that the test data indicate an observable amount of leakage through the confining beds. Witherspoon and Neumann (1972) discuss in some detail the theory and procedure for analysis of leaky confining beds and give two field examples from gas storage projects.

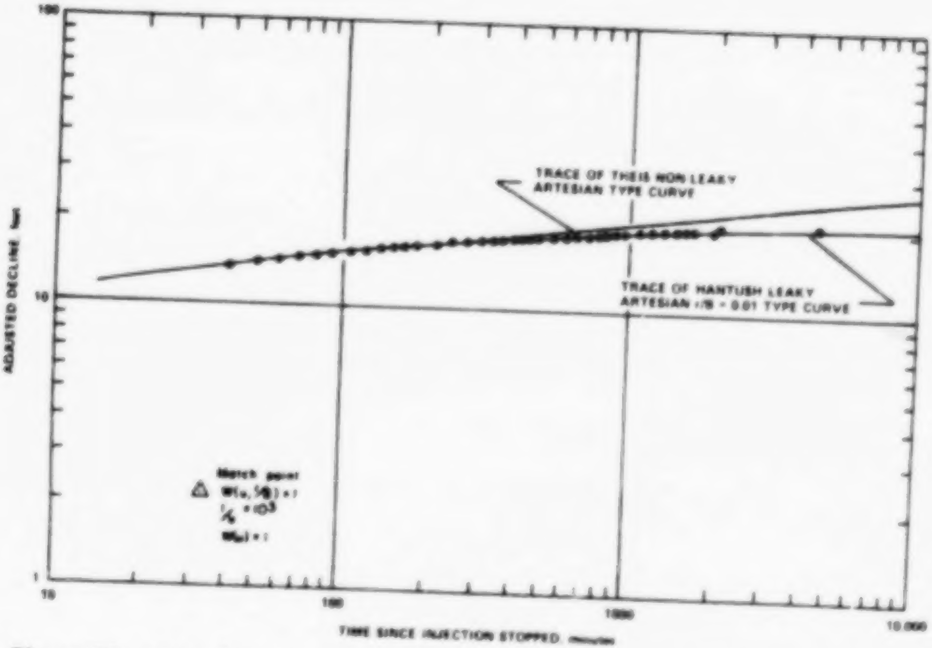


Figure 29. Plot of recovery data and matching-type curves for an injection test of a well at Mulberry, Florida (Wilson et al., 1973).

Readers wishing to pursue the subject of aquifer testing further are referred to the same references previously given for drill-stem test analysis, particularly to the Society of Petroleum Engineers Monograph prepared by Matthews and Russell (1967). Additionally, publications in the groundwater field by Lohman (1972) and Kruseman and De Ridder (1970) are excellent recent summaries of this subject, as is the reference by Witherspoon et al. (1967), which was prepared for the underground gas storage industry.

SECTION VI

PREDICTION OF AQUIFER RESPONSE

FLOW THEORY

The basic equation used to describe the flow of fluids in porous media is Darcy's law, alternate forms of which are given on page 25 by Equations 3, 4, and 5. Darcy's law alone can be used for calculations of steady flow. Steady flow occurs when the same quantity of fluid is entering an aquifer as is leaving it, so that no change in volume of the aquifer or its contained fluid is occurring with time.

When flow is unsteady or, as stated in oil field terminology, when formation pressures are transient, Darcy's law must be combined with the continuity equation so that time and the compressibility of the aquifer and aquifer fluids may be taken into account. The appropriate partial differential equation and its derivation may be found in most modern texts on hydrogeology and petroleum reservoir engineering, along with numerous solutions.

The solution first formulated and still most widely used is that for a well pumping from or injecting into an aquifer under the following conditions:

1. The aquifer is, for practical purposes, infinite in areal extent
2. The aquifer is homogeneous, isotropic, and of uniform thickness over the area of influence
3. Natural flow in the aquifer is at a negligible rate
4. The aquifer is sufficiently confined so that flow across confining beds is negligible
5. The well penetrates the entire thickness of the aquifer
6. The well is small enough that storage in the well can be neglected and water removed from storage in the aquifer is discharged instantaneously.

This is a formidable list of assumptions, which are obviously not completely met in any real situation. However, if one reviews the characteristics of aquifers such as the Mt. Simon Formation, it can be concluded that they probably comply with the assumptions sufficiently for practical purposes.

The equation that describes the response of such an aquifer to a single injection well is then:

$$\Delta h = \frac{Q}{4\pi T}\left(-0.577216 - \log_e u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \ldots\right) \text{ (L)} \qquad (15)$$

where

$$u = \frac{r^2 S}{4Tt} \quad \text{(dimensionless)}$$

and Δh = hydraulic head change at radius r and time t
Q = injection rate
T = transmissivity
S = storage coefficient
t = time since injection began
r = radial distance from well bore to point of interest.

One can easily enter the desired values into this series solution, or tables with the series evaluated are available in the previously referenced publications on aquifer testing.

For large values of time, small values of radius of investigation, or both, Equation 15 can be reduced to:

$$\Delta h = \frac{2.30Q}{4\pi T} \log \frac{2.25Tt}{r^2 S} \quad \text{(L)} \quad . \qquad (16)$$

Equations 15 and 16 are not dimensionalized; therefore, any consistent units can be used.

Two very important characteristics of the equations presented above are that individual solutions can be superimposed, and that hydrologic boundaries such as faults can be simulated by a properly located imaginary well. The fact that solutions can be superimposed allows the effects of multiple wells to be easily analyzed. Because the effect of boundaries is analogous to that of properly located pumping or injection wells, the existence of boundaries can be detected by observing aquifer response to injection or pumping or, conversely, the effects of known or suspected boundaries can be estimated.

REGIONAL FLOW

As examples of the application of Darcy's law to analysis of regional flow, the velocity of natural flow in the Mt. Simon Formation in Ohio and the lower Floridan aquifer in Florida will be considered.

From Figure 18 (page 30) it can be seen that, at the location of the Empire-Reeves injection well, the hydraulic gradient is 8 feet per mile toward the northwest. At this location, the Mt. Simon Formation has a permeability of 24 millidarcys (from a drill-stem test) and a porosity of 10.4 percent (Clifford, 1973). Rearranging Darcy's law:

$$\bar{v} = \frac{Q}{A} = K \frac{dh}{dL} \quad (L/T) \tag{17}$$

where $\bar{v}$ = apparent velocity through entire area A.

Then,

$$v = \frac{\bar{v}}{\phi} = \frac{Q}{A\phi} = \frac{K}{\phi} \frac{dh}{dL} \tag{18}$$

where v = average velocity of flow through pores
ϕ = porosity.

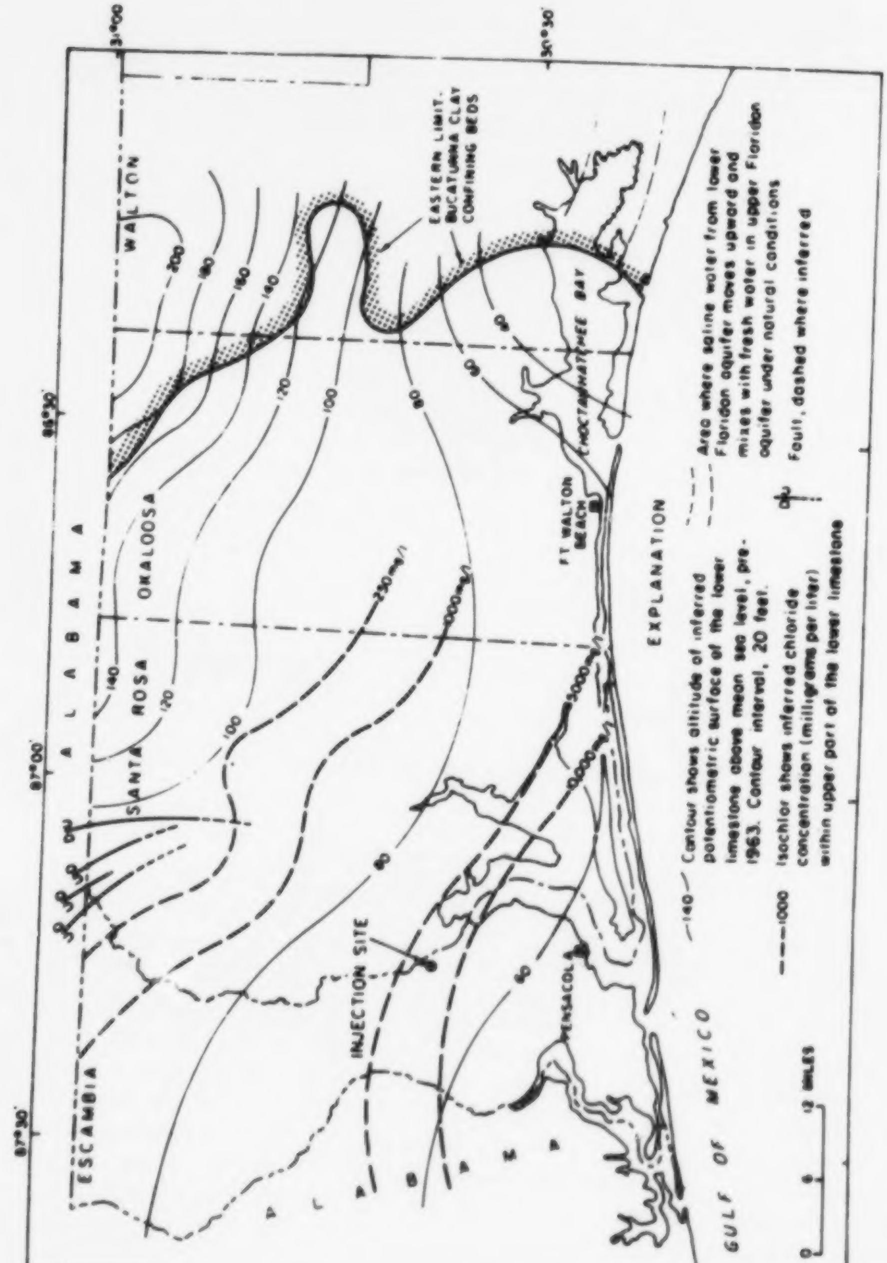
From the data given above, converted to consistent units, and entered into Equation 18

$$v = \frac{21.3639 \text{ ft/yr}}{0.104} \times \frac{8 \text{ ft/mile}}{5,280 \text{ ft/mile}}$$

$$= 0.31 \text{ ft/yr} \quad .$$

This evaluation shows that water in the Mt. Simon Formation in north-central Ohio is moving northwest at a rate of 0.31 ft/yr. The source of the hydraulic gradient and the fate of the moving water are not understood. Furthermore, there are complications in the analysis itself, as pointed out by Bond (1973). However, in spite of such uncertainties, it can be indisputably concluded that water in the Mt. Simon Formation is moving at a negligible rate, if at all, at this location. This fact is sufficient for a practical analysis of the monitoring needed at such a wastewater injection site.

As a further example, Figure 30 shows the potentiometric surface for the lower Floridan aquifer in northwest Florida. There the hydraulic gradient was estimated to be about 1.33 ft/mile toward the southwest in the vicinity of the Monsanto Company injection well prior to its operation.


31°00'
30°30'
87°30'
87°00'
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A L A B A M A
ESCAMBIA
SANTA ROSA
OKALOOSA
WALTON
INJECTION SITE
PENSACOLA
FT. WALTON BEACH
CHOCTAWHATCHEE BAY
EASTERN LIMIT, BUCATUNNA CLAY CONFINING BEDS
GULF OF MEXICO
250 mg/l
1000 mg/l
5000 mg/l
10000 mg/l
200
180
160
140
120
100
80
60
EXPLANATION
—140— Contour shows altitude of inferred potentiometric surface of the lower limestone above mean sea level, pre-1963. Contour interval, 20 feet.
—1000— Isochlor shows inferred chloride concentration (milligrams per liter) within upper part of the lower limestone
Area where saline water from lower Floridan aquifer moves upward and mixes with fresh water in upper Floridan aquifer under natural conditions
Fault, dashed where inferred
D U
0 6 12 MILES

Figure 30. Hydrogeology of the lower Floridan aquifer in northwest Florida (Goolsby, 1972).

The permeability is about one darcy and the porosity is estimated to be 10 percent (Goolsby, 1971 and 1972). The velocity of natural flow in the lower Floridan aquifer is then estimated to be

$$v = \frac{890 \text{ ft/yr}}{0.10} \times \frac{1.33 \text{ ft/mile}}{5,280 \text{ ft/mile}} = 2.24 \text{ ft/yr} \quad .$$

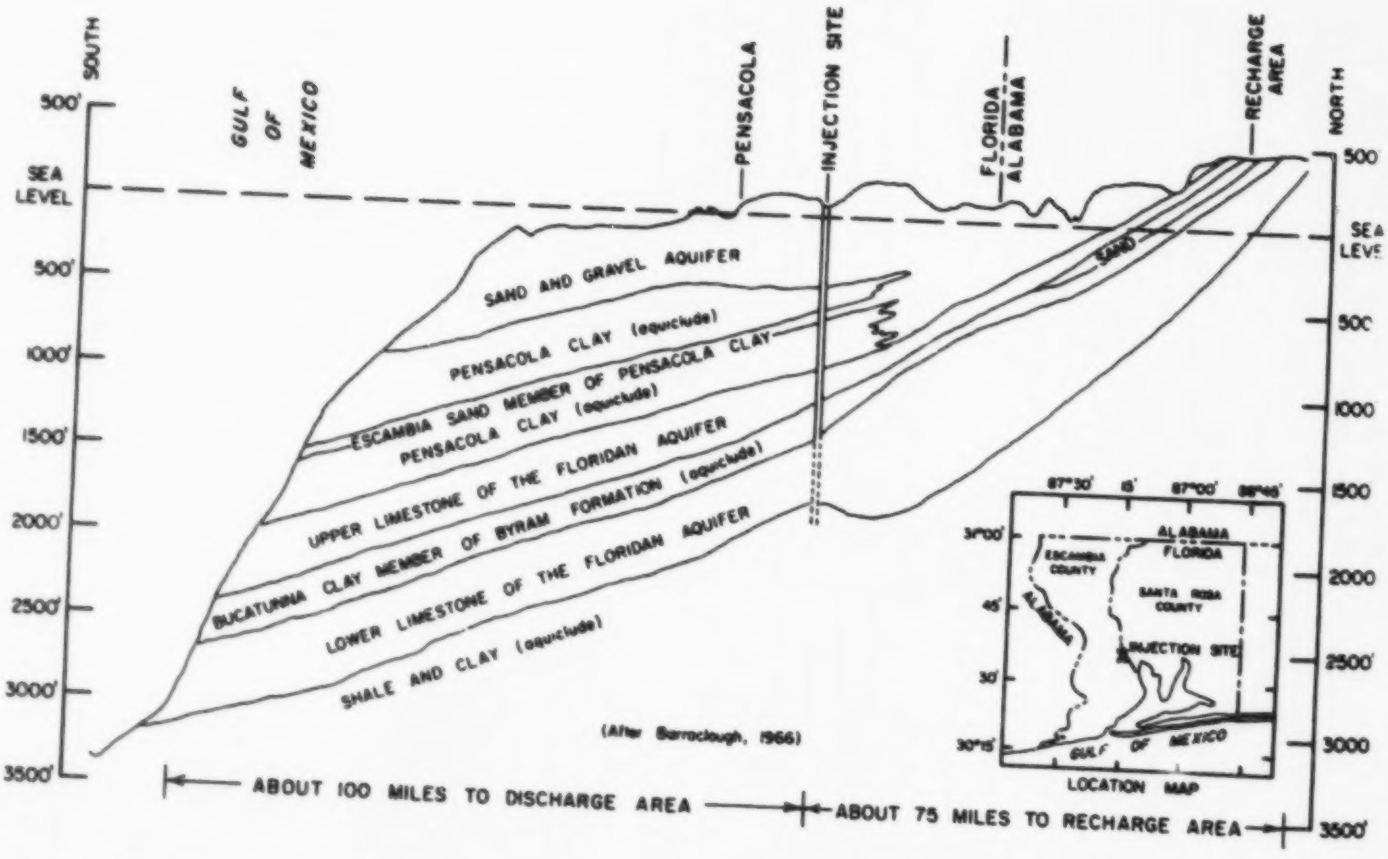
This analysis is more easily interpreted than the previous one for Ohio, because it is well known that the source of hydraulic head lies to the north of the injection well site and that the discharge area lies to the south as shown in Figure 31. The velocity of flow is again very low; it appears that more than 200,000 years would be required for injected waste to reach the subsea discharge point 100 miles to the south.

PRESSURE EFFECTS OF INJECTION

Wastewater injected into deep aquifers does not move into empty voids; rather it displaces existing fluids, primarily saline water. The displacement process requires exertion of some pressure, in excess of the natural formation pressure. The pressure increase is greatest at the injection well and decreases in approximately a logarithmic manner away from the well. The amount of excess pressure required and the distance to which it extends depend on the properties of the formation and the fluids, the amount of fluid being injected, and the length of time that injection has been going on. The pressure or head changes resulting from injection are added to the original regional hydraulic gradients to obtain a new potentiometric surface map that depicts the combined effects of regional flow and the local disturbances.

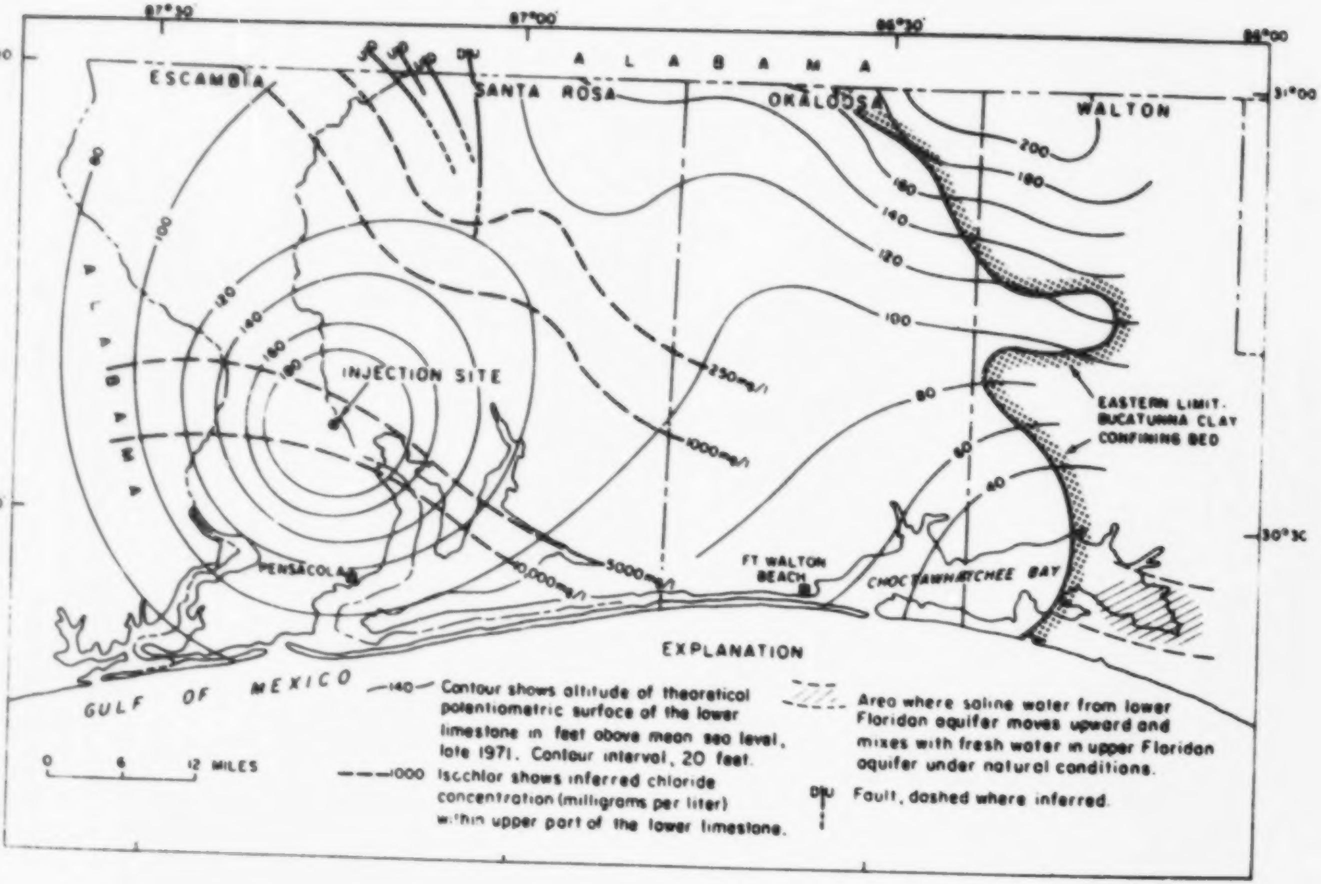
By use of the theory that has been described, potentiometric surface maps can be produced to show the anticipated situation at any time in the future. If observation wells exist, the actual potentiometric surface at any time can be constructed from the water levels or pressures recorded in the wells.

Figure 32 shows the theoretical potentiometric surface map for the lower Floridan aquifer in northwestern Florida in 1971, after wastewater injection had been in progress near Pensacola for about eight years. The estimated pressure effects of injection can be seen by comparing Figure 30 with Figure 32. The comparison indicates that changes in hydraulic head may extend out for 30 miles or more from the injection site. Although Figure 32 is titled a theoretical potentiometric surface map, it is, in fact, partially substantiated by observation wells. If more observation wells were available, the map would be constructed entirely from observed data.


SOUTH
NORTH
500'
SEA LEVEL
500'
1000'
1500'
2000'
2500'
3000'
3500'
GULF OF MEXICO
PENSACOLA
INJECTION SITE
FLORIDA
ALABAMA
RECHARGE AREA
SAND AND GRAVEL AQUIFER
PENSACOLA CLAY (aquiclude)
ESCAMBIA SAND MEMBER OF PENSACOLA CLAY
PENSACOLA CLAY (aquiclude)
UPPER LIMESTONE OF THE FLORIDAN AQUIFER
BUCATUNNA CLAY MEMBER OF BYRAM FORMATION (aquiclude)
LOWER LIMESTONE OF THE FLORIDAN AQUIFER
SHALE AND CLAY (aquiclude)
SAND
ABOUT 100 MILES TO DISCHARGE AREA
ABOUT 75 MILES TO RECHARGE AREA
87°30'
15'
87°00'
86°45'
31°00'
45'
30'
30°15'
ALABAMA
FLORIDA
ESCAMBIA COUNTY
SANTA ROSA COUNTY
INJECTION SITE
GULF OF MEXICO
LOCATION MAP

(After Barraclough, 1966)

Figure 31. Generalized north–south geologic section through southern Alabama and northwestern Florida (Goolsby, 1972).


87°30'
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ALABAMA
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SANTA ROSA
OKALOOSA
WALTON
INJECTION SITE
PENSACOLA
FT WALTON BEACH
CHOCTAWHATCHEE BAY
GULF OF MEXICO
EASTERN LIMIT, BUCATUNNA CLAY CONFINING BED
250mg/l
1000mg/l
5000mg/l
10,000mg/l
200
180
160
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80
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0 6 12 MILES
EXPLANATION
140 Contour shows altitude of theoretical potentiometric surface of the lower limestone in feet above mean sea level, late 1971. Contour interval, 20 feet.
1000 Isochlor shows inferred chloride concentration (milligrams per liter) within upper part of the lower limestone.
Area where saline water from lower Floridan aquifer moves upward and mixes with fresh water in upper Floridan aquifer under natural conditions.
D U Fault, dashed where inferred.

Figure 32. Theoretical potentiometric surface of lower limestone of Floridan aquifer in late 1971 (Goolsby, 1972).

As an example of the development of such a theoretical potentiometric surface map, one point on Figure 32 will be determined. The point will be one at a radial distance of 6 miles northeast of the injection well site, which places it at a potential of about 77 feet on Figure 30 and 180 feet on Figure 32, showing a head increase of about 103 feet. From Goolsby (1972), the following data were obtained or estimated:

$Q = 2.427 \times 10^6$ gal/day $= 3.244 \times 10^5$ ft^3/day

$T = 6,300$ gal/day·ft $= 842$ ft^3/day·ft

$t = 3,000$ days

$r = 6$ miles $= 31,680$ ft

$S = 2 \times 10^{-4}$ (dimensionless) .

Therefore, from Equation 16, the head increase in 3,000 days 6 miles northeast of the injection site is:

$$\Delta h = \frac{2.30 \times 3.244 \times 10^5 \text{ ft}^3/\text{day}}{4\pi \times 842 \text{ ft}^3/\text{day}\cdot\text{ft}}$$

$$\times \log \frac{2.25 \times 842 \text{ ft}^3/\text{day}\cdot\text{ft} \times 3,000 \text{ days}}{(31,680 \text{ ft})^2 \times 2 \times 10^{-4}}$$

$$= 70.50 \log 28.31 = 102.4 \text{ ft} \quad .$$

The calculated increase of 102.4 feet compares very well with the 103 feet obtained from Goolsby's maps. As many points as desired can be calculated to produce the contour map. Rather than calculating the pressure at a point (actually on a circle with radius r) even head increments can be selected and the radii to them calculated, which simplifies the contouring process.

The well in Ohio for which core data are available, and for which a drill-stem test and an injection test were presented, will also be used as an example. The core data yielded a transmissivity of 954 millidarcy-ft/centipoise, the drill-stem test 345 millidarcy-ft/centipoise, and the injection test 452 millidarcy-ft/centipoise. The value from the injection test will be used, because it is considered the most reliable. Pressure buildup will be calculated at the well, which, as previously explained, appears to have an effective radius of 8.7 ft. The storage coefficient calculated from Equation 7 is 3.34×10^{-4}. The information of interest is, for injection rates of 25, 50, or 75 gpm, how long can wastewater be injected before a limiting allowable surface pressure increase of 1800 psi has been reached? Rearranging Equation 16, and entering the values given above, which have been converted to consistent units:

$$\log t = \frac{4\pi\ T\ \Delta h}{2.30Q} - \frac{\log 2.25T}{r^2 S}$$

$$\log t = \frac{(4\pi)\ (1.24\ \text{ft}^2/\text{day})\ (4157\ \text{ft})}{(2.30)\ (14{,}437\ \text{ft}^3/\text{day})} - \log \frac{(2.25)\ (1.24\ \text{ft}^2/\text{day})}{(8.7\ \text{ft})^2\ (3.34 \times 10^{-4})}$$

$$\log t = 1.95 - \log 110.36 = -0.092$$

$$t = 0.81\ \text{days} = 19.4\ \text{hours.}$$

This value could also have been obtained by extrapolating to 1800 psi the line in Figure 28 (page 50), but only for the same injection rate and radius of investigation and not for other rates and radii.

As the injection rate is changed the amount of time required for the pressure to increase to a particular level changes proportionately, so that for an injection rate of 50 gpm, t = 27 hours, and for an injection rate of 25 gpm, t = 54 hours.

For this well, the calculations simply confirm what could already have been intuitively deduced; the fact that the Mt. Simon Formation will not be a suitable injection unit at this location. Similar calculations could have been made from core data and from the drill-stem test and this conclusion reached prior to injection testing.

In comparison with the Ohio example, a well in northern Illinois had the following characteristics:

b = 1734 ft
$\overline{K}_{av.}$ = 36 millidarcys
T = 62.42 darcy·ft
Q = 100 gpm
r_{well} = 4.4 in.
S = 5.46×10^{-3} .

Using these data, what will be the injection pressure increase at the well after 5 years of continuous operation?

$$\Delta p = 0.433\ \text{psi/ft} \left[\frac{2.30 \times 19{,}248\ \text{ft}^3/\text{day}}{4\pi \times 167\ \text{ft}^2/\text{day}} \times \log \frac{2.25 \times 1825\ \text{days} \times 167\ \text{ft}^2/\text{day}}{(0.36\ \text{ft})^2 \times 5.46 \times 10^{-3}} \right] = 81\ \text{psi}\ .$$

This calculation shows that the pressure increase will be negligible. In actual operation, the injection pressure has averaged 120 to 300 psi; the difference between predicted and observed performance is not of concern in this case unless the observed pressure continues to increase, indicating possible progressive plugging of the formation.

Multiple Wells

As previously mentioned, estimating the combined pressure effects of multiple wells is made easy by virtue of the principle of superposition. It is only necessary to estimate the separate effects of two or more wells at the point of interest, then to add them to obtain their combined effect. For example, referring to the last Mt. Simon well discussed above, what would the combined effects of two wells spaced 1,000 feet apart be on each other after 5 years? Assume both wells have the same characteristics:

$$\Delta p = 81 \text{ psi} + 0.433 \text{ psi/ft} \left[\frac{2.30 \times 19{,}248 \text{ ft}^3/\text{day}}{4\pi \times 167 \text{ ft}^2/\text{day}} \times \log \frac{2.25 \times 1825 \times 167 \text{ ft}^2/\text{day}}{(1000 \text{ ft})^2 \times 5.46 \times 10^{-3}}\right]$$

$$\Delta p = 81 \text{ psi} + 19 \text{ psi} = 99 \text{ psi} \quad .$$

Hydrologic Discontinuities

Another common situation is one in which a barrier to flow, a fault or facies change, is present within the area of influence of an injection well. Faults may also act as channels for escape of fluid from the injection horizon.

In predicting aquifer response in the presence of such features, the image-well concept is used. Assume the presence of a fault or lithologic change that acts as an impermeable barrier, 500 feet in any direction from the Mt. Simon Formation injection well that is discussed above. Then, according to image-well theory, an imaginary injection well with all of the same properties as the real injection well is placed 1,000 feet from the real well, on the opposite side of the fault and on a line that passes through the real well and is perpendicular to the fault. Figure 33 shows the potentiometric surface and flow lines that would develop in such a situation; the pressure effect of the barrier would be the same as that calculated above for an actual injection well 1,000 feet from the first well.

If the hydrologic discontinuity were a leaky fault rather than a sealed one, the opposite effect would occur; the pressure at any time would be reduced as if a discharging well were present.

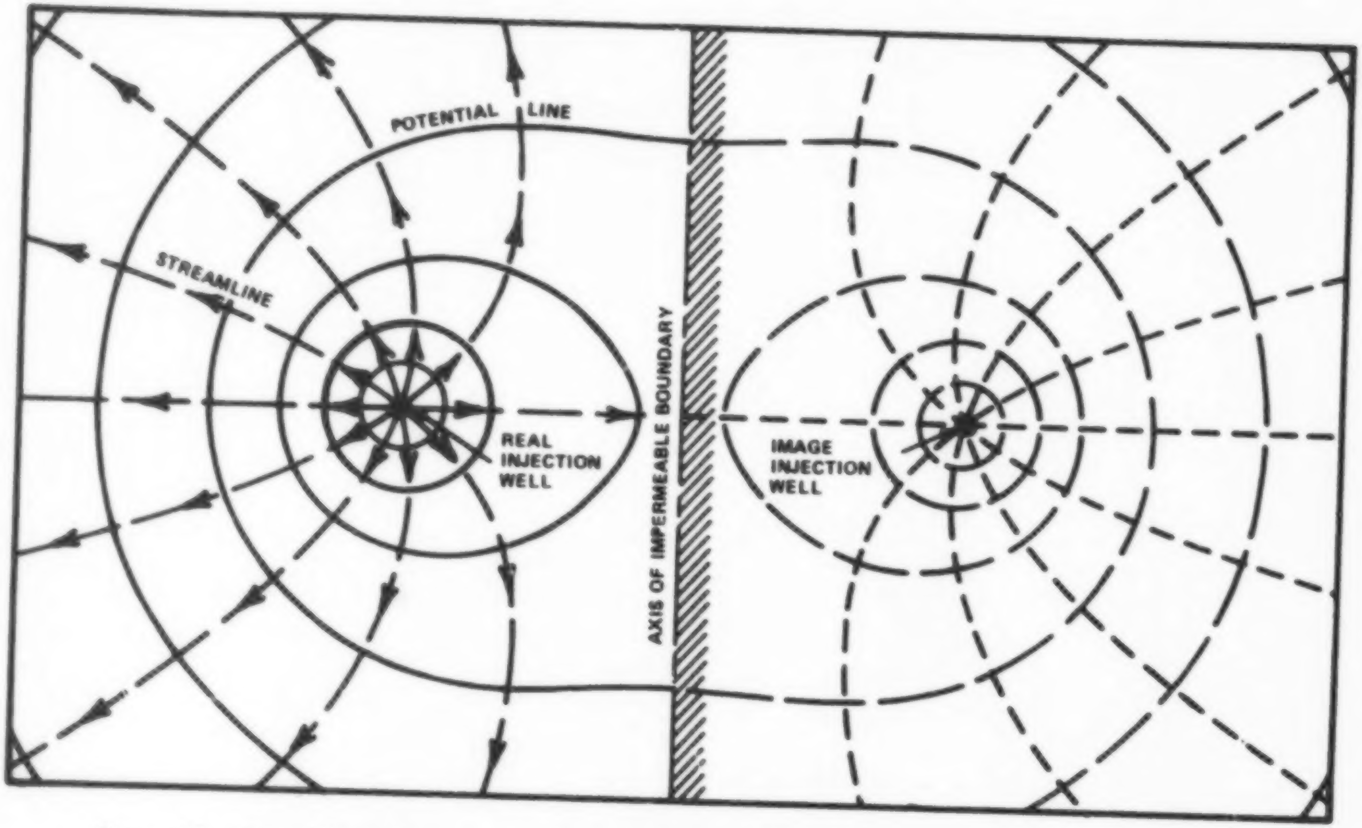

POTENTIAL LINE
STREAMLINE
REAL INJECTION WELL
AXIS OF IMPERMEABLE BOUNDARY
IMAGE INJECTION WELL

Figure 33. Generalized flow net showing the potential lines and stream lines in the vicinity of an injection well near an impermeable boundary (Ferris et al., 1962).

The equations and examples given are for the most basic hydrogeologic circumstances, but many injection wells can be treated this way because these are the conditions sought when choosing an injection site and receiving aquifer. However, cases of virtually any complexity can be analyzed by use of the appropriate solution to the basic flow equations; where analytical solutions are not possible, numerical models can be developed. The limitations to an analysis are usually pragmatic rather than theoretical —lack of data, limitations of time and funds, or the fact that a simplified estimate is sufficient for the circumstances.

RATE AND DIRECTION OF FLUID MOVEMENT

As with pressure response to injection, the rate and direction of movement of the injected fluid depend on the hydrogeology of the site; therefore, the same factors previously listed require consideration. In addition, the properties of the formation water and the injected wastewater assume major importance.

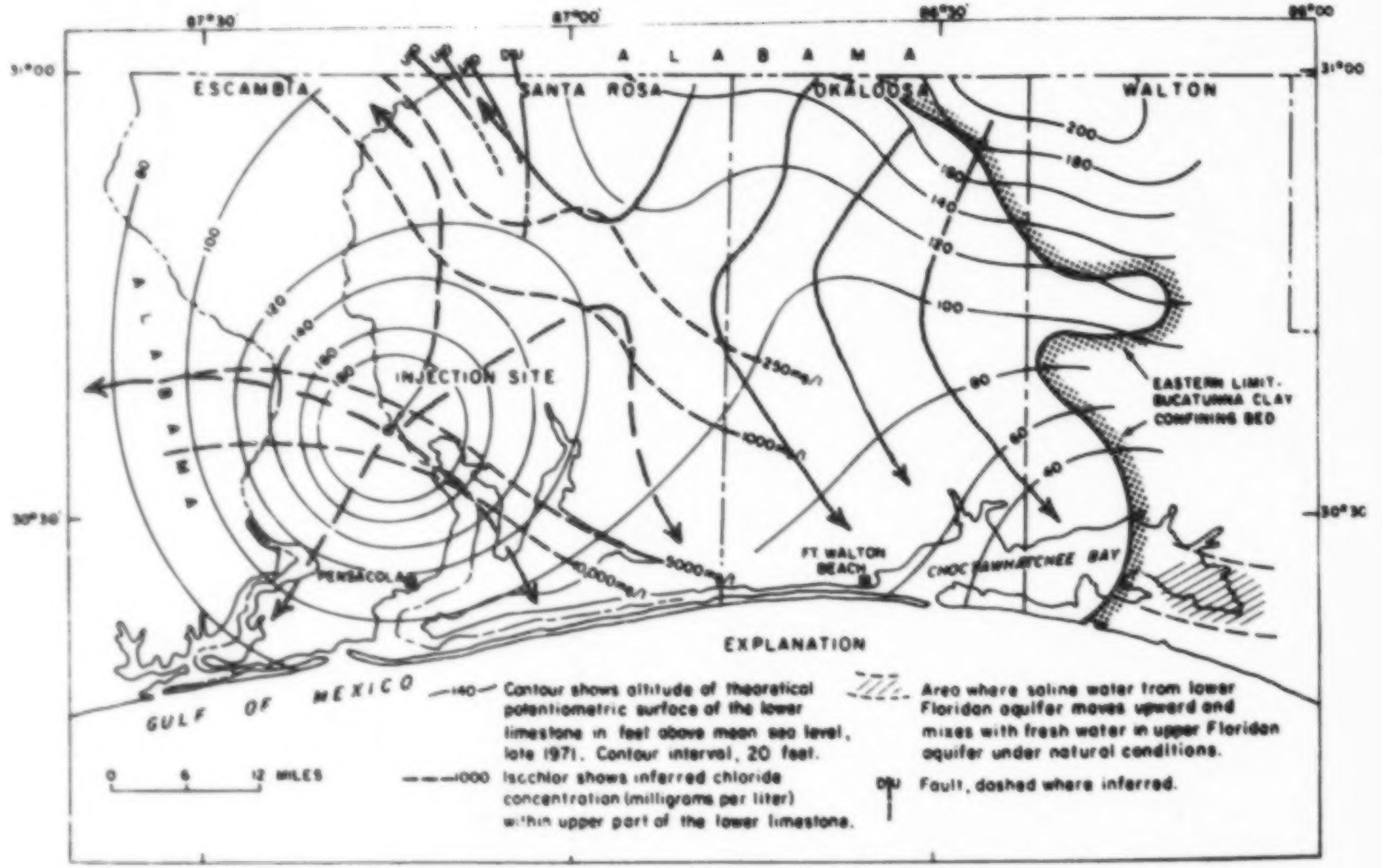
Broad flow patterns in an aquifer with a significant existing potentiometric gradient can be deduced from a map of the regional potentiometric surface with the effects of the injection system superimposed.

Figure 34 is a duplication of Figure 32, with flow lines added to show how the flow directions of aquifer water and injected wastewater can be deduced from the potentiometric surface map. The wastewater will never actually travel as far northward as the map indicates, but displaced aquifer water will be forced in this direction, ahead of the small cylinder of wastewater that surrounds the well. The extent of this wastewater cylinder will be discussed next.

A good estimate of the minimum distance of wastewater flow from an injection well can be made by assuming that the wastewater will uniformly occupy an expanding cylinder with the well at the center. The equation for this case is:

$$r = \sqrt{\frac{V}{\pi b \phi}} \quad (L) \qquad (19)$$

where r = radial distance of wastewater front from well
$V = Qt$ = cumulative volume of injected wastewater
b = effective aquifer thickness
ϕ = average effective porosity.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ALABAMA
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SANTA ROSA
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WALTON
INJECTION SITE
PENSACOLA
FT. WALTON BEACH
CHOCTAWHATCHEE BAY
GULF OF MEXICO
EASTERN LIMIT, BUCATUNNA CLAY CONFINING BED
200
180
160
140
120
100
80
60
250mg/l
1000mg/l
5000mg/l
10,000mg/l
D U
0 6 12 MILES
EXPLANATION
140 Contour shows altitude of theoretical potentiometric surface of the lower limestone in feet above mean sea level, late 1971. Contour interval, 20 feet.
1000 Isochlor shows inferred chloride concentration (milligrams per liter) within upper part of the lower limestone.
Area where saline water from lower Floridan aquifer moves upward and mixes with fresh water in upper Floridan aquifer under natural conditions.
Fault, dashed where inferred.

Figure 34. Theoretical potentiometric surface of lower limestone of Floridan aquifer in late 1971, with flow lines showing the directions of aquifer water and wastewater movement. Solid flow lines show the direction of flow of diverted aquifer water, dashed flow lines show direction of flow of injected wastewater and displaced aquifer water (modified after Goolsby, 1972).

For a Mt. Simon injection well with the following characteristics:

Q = 100 gpm

t = 5 years

b = 1618 feet

ϕ = 13.5 percent

$$r = \sqrt{\frac{35,128,993 \text{ ft}^3}{\pi \times 1618 \text{ ft} \times 0.135}}$$

$$= 226 \text{ ft} \quad .$$

It is noted that effective aquifer thickness and average effective porosity should be used. The effective aquifer thickness is, for example, that part of the total aquifer that consists of sandstone in the case of a mixed sandstone-shale lithology. The effective porosity has been previously defined as that part of the porosity in which the pores are interconnected.

In most situations the minimum radial distance of travel will be exceeded, because of dispersion, density segregation, and channeling through high permeability zones. Flow may also be in a preferred direction, rather than radial, because of hydrologic discontinuities (e.g., faults), selectively oriented permeability paths, or natural flow gradients.

An estimate of the influence of dispersion can be made with the following equation:

$$r' = r + 2.3\sqrt{Dr} \quad (L) \tag{20}$$

where r' = radial distance of travel with dispersion

D = dispersion coefficient; 3 ft for sandstone aquifers and 65 feet for limestone or dolomite aquifers.

Equation 20 is obtained by solving equation (10.6.65) of Bear (1972) for the radial distance at which the injection front has a chemical concentration of 0.2 percent of the injected fluid.

The detailed development of dispersion theory is presented by Bear (1972). The dispersion coefficients given are high values for sandstone and limestone aquifers obtained from the literature. No actual dispersion coefficients are known to have been obtained for any existing injection well.

Then, for the above example, which is a sandstone:

$$r' = 226 \text{ ft} + 2.3 \sqrt{3 \text{ ft} \times 226 \text{ ft}}$$

$$= 286 \text{ ft} \ .$$

It is clear that, in this example, the distance of wastewater travel from the well is negligible and could not possibly be of concern if actual conditions comply even generally with those that were assumed. This conclusion has been found to apply to many of the wells that have been constructed to date. Since almost no attempts have been made to determine the actual wastewater distribution around existing injection wells, there is little evidence for comparison with theory. However, if such a calculation were in error by several hundred percent, there would still be no cause for concern, since the injection well, in this and many other cases, is tens of miles from the nearest other well penetrating the injection zone.

To proceed beyond the calculations that have been shown may not be necessary or, in many cases, meaningful. However, it may be possible, if necessary, to account for some of the additional complications that are mentioned. For example, Bear and Jacobs (1964), in one of a series of reports, considered the flow of water from a groundwater recharge well in an aquifer of uniform flow, when the densities and viscosities of the injected and interstitial fluids are the same. Gelhar and others (1972) developed analytical techniques for describing the mixing of injected and interstitial waters of different densities.

So far, the travel of the injected wastewater has been treated as though it were an inert fluid and would not react with the aquifer water or minerals, be affected by bacterial action, or decompose or radioactively decay. If the wastewater is not inert, then changes in chemical composition with time and distance may also need to be considered. Bredehoeft and Pinder (1972) discuss the methodology for a unified approach to this type of problem and Robertson and Barraclough (1973) presented an example of a case in which radioactive decay, dispersion, and reversible sorption were considered. However, no procedure exists at this time for simultaneously considering the full range of practical possibilities that may be involved in wastewater movement.

In spite of the degree of sophistication used in development of theories for rate and direction of travel of injected fluid from an injection well, nonuniform distribution of porosity and permeability will preclude making accurate estimates in many cases. In general, wastewater flow in unfractured sand or sandstone aquifers would be expected to more closely agree with theory than flow in fractured reservoirs or in carbonate aquifers with solution permeability. However, even in sand aquifers, flow can be expected to be non-ideal as shown by tests reported by Brown and Silvey (1973). Particularly great deviations from predictions may occur in limestone or dolomite aquifers. Figure 35 is an example of this. The radial zones around Well No. 1 show the predicted extent of waste travel using Equations 19 and 20. The irregular boundary shows the probable actual extent of wastewater spread as indicated by evidence from Wells 2 and 3. In this case, the wastewater apparently traveled selectively in a single thin porous and permeable interval rather than throughout the several zones indicated by testing results. Accurate prediction of the rate and direction of movement in such a case may well be technically infeasible even in the future because the amount of information needed will seldom, if ever, be available.

HYDRAULIC FRACTURING

Hydraulic fracturing may be deliberately accomplished to increase formation permeability or it may occur during injection testing or wastewater injection if the fracture initiation pressure is exceeded. Regulatory policy may or may not allow short-term hydraulic fracturing operations for well stimulation, but continuous injection at pressures above the fracture point are prohibited by most, if not all, agencies. This is because of the danger

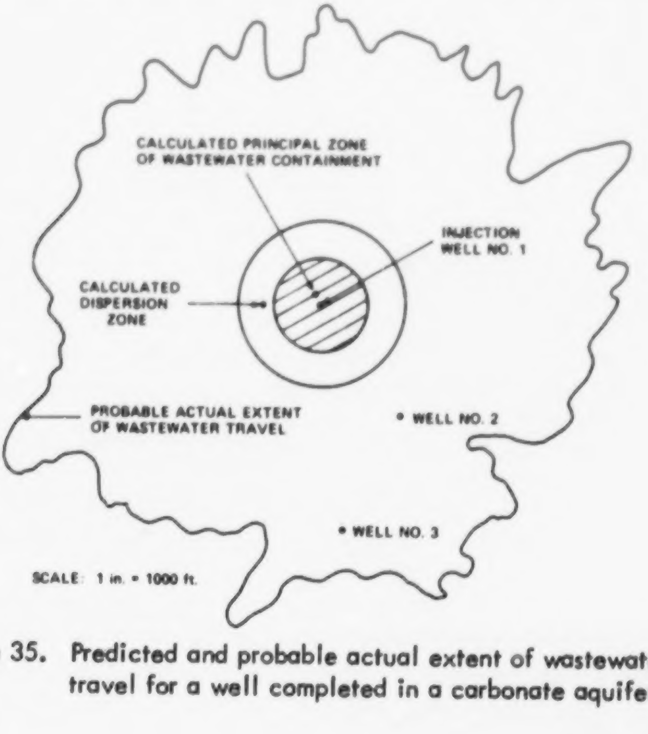
CALCULATED PRINCIPAL ZONE OF WASTEWATER CONTAINMENT
INJECTION WELL NO. 1
CALCULATED DISPERSION ZONE
PROBABLE ACTUAL EXTENT OF WASTEWATER TRAVEL
WELL NO. 2
WELL NO. 3
SCALE: 1 in. = 1000 ft.

Figure 35. Predicted and probable actual extent of wastewater travel for a well completed in a carbonate aquifer.

of damage to well facilities and because of the uncertainty about where the fractures and injected fluids are going as fractures continue to be extended.

Figure 36 is a schematic diagram of bottom-hole pressure versus time during hydraulic fracturing. Before injection begins, the pressure is that of the formation fluid (p_o) and the column of fluid in the well bore. Pressure is increased until fracturing occurs; then, as fluid continues to be pumped into the well, the pressure stabilizes at p_f, the flowing pressure, during which the fractures continue to be extended. When injection is ceased, and the well shut in, the pressure quickly stabilizes to a constant value, the instantaneous shut-in pressure. This pressure is considered to be equal to the least principal earth stress in the vicinity of the well.

In estimating the fluid pressure at which hydraulic fracturing will occur one of two conditions is usually assumed:

1. That the least principal stress is less than the vertical lithostatic stress caused by the rock column. In this case fractures are assumed to be vertical.
2. That the vertical lithostatic stress is the least principal stress. In this case fractures will be horizontal.

In the first case, the minimum bottom-hole pressure required to initiate a hydraulic fracture can be estimated from (Hubbert and Willis, 1972):

$$p_i \cong \frac{S_z + 2p_o}{3} \qquad (F/L^2) \qquad (21)$$

where p_i = fracture initiation pressure
S_z = total lithostatic stress
p_o = formation fluid pressure.

The fracture gradient, that is, the injection pressure required per foot of depth, can be estimated by entering representative unit values into Equation 21. The unit values for S_z and p_o are, respectively, 1.0 and 0.46 psi/ft. This yields a p_i gradient of 0.64 psi/ft as a minimum value for initiation of hydraulic fractures. This situation implies a minimum lateral earth stress. As the lateral stresses increase, the bottom-hole fracture initiation pressure also increases up to a limiting value of 1.0 psi/ft. Actually, fracture pressures may exceed 1.0 psi/ft when the rocks have significant tensile strength and no inherent fractures that pass through the well bore. In any particular case, injection tests can be run to determine what the actual fracture pressure is, then operating injection pressures held below the instantaneous shut-in pressure. In the absence of any

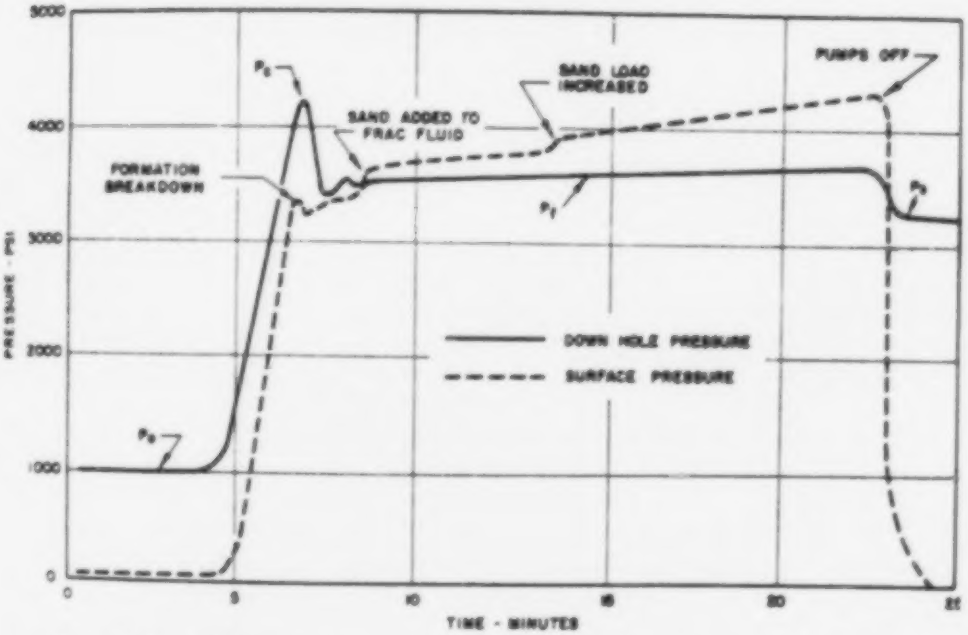

Figure 36. Schematic diagram of pressure versus time during hydraulic fracturing (Kehle, 1964).

specific data, arbitrary limitations of from 0.5 to 1.0 psi per foot of depth have been imposed on operating injection wells. Regional experience should be used as a criterion in establishing an arbitrary limit, since regional tectonic conditions and fluid pressure gradients dictate what a safe limit will be.

GENERATION OF EARTHQUAKES

As a matter of background, it is widely, but not universally, accepted that a series of earthquakes that began in the Denver area in 1962 was initiated by injection of wastewater into a well at the Rocky Mountain Arsenal. Since the association of seismic activity with wastewater injection at Denver, apparently similar situations have been observed at Rangely, Colorado, and Dale, New York. The former related to water injection for secondary recovery of oil and the latter to disposal of brine from solution mining of salt. On the other hand, there are presently about 160 operating industrial wastewater injection wells and tens of thousands of oil field brine disposal wells that have apparently never caused any noticeable seismic disturbance, so these three examples would have to be considered very rare.

It has been erroneously stated by many that the seismic events have been stimulated by "lubrication" of a fault zone by injected fluids. What has happened, if injection has been involved, is that the water pressure on a fault plane has been increased, thus decreasing the friction on that plane and allowing movement and consequent release of stored seismic energy.

Based on this interpretation of the mechanism of earthquake triggering by fluid injection, some of the conditions that would have to exist in order to have such earthquakes would be:

1. A fault with forces acting to cause movement of the blocks on either side of the fault plane, but which are being successfully resisted by frictional forces.
2. An injection well that is constructed close enough, vertically and horizontally, to the fault so that the fluid pressure changes caused by injection will be transmitted to the fault plane.
3. Injection at a sufficiently great rate and for a sufficiently long time to increase fluid pressure on the fault plane to the point that frictional forces resisting movement become less than the forces tending to cause movement. At this time, movement will occur and stored seismic energy will be released. That is, an earthquake will occur.

As has been discussed earlier in the section on state of stress, relatively little is known about stress distribution in the earth's crust and even less is known about stress distribution along fault systems. In the absence of this information, only qualitative estimates of the probability of earthquake stimulation can be made. In the great majority of cases the potential for earthquake stimulation will be nonexistent or negligible because only very limited areas in the country are susceptible to earthquake occurrence. The susceptible areas are delineated by records of earthquakes that have occurred in the past and by tectonic maps that show geologic features which are associated with belts of actual or potential earthquake activity.

In a case where subsurface stresses are known or are determined by hydraulic fracturing or other means, and where the location and orientation of the fault plane are known, then a quantitative estimate of the pressure required to cause fault movement can be made. Raleigh (1972) provides an example of such a calculation from the Rangely, Colorado, oil field.

SECTION VII

SURVEILLANCE OF OPERATING WELLS

INJECTION WELL MONITORING

The principal means of surveillance of wastewater injection that is presently practiced is monitoring at the injection well of the volume, chemistry, and biology of the injected wastewater and of the well-head and annulus pressures (Figure 37). To some this apparently seems inadequate. However, if all of the necessary evaluations have been made during the planning, construction, and testing of the well, then this may be a satisfactory program when combined with periodic inspection of surface and subsurface facilities. This is because, as pointed out by Talbot (1972), the greatest risk of escape of injected fluids is normally through the injection well itself, rather than from leakage through permeable confining beds, fractures, or unplugged wells.

The purpose of monitoring the volume of injected wastewater is to allow for estimates of the distance of wastewater travel, to allow for interpretation of pressure data, and to provide a permanent record of the volume of emplaced wastewater. Also, a record is needed as evidence of compliance with restrictions, for interpretation of well behavior, and as a precaution in the event that a chemical parameter should deviate from design specifications. Some characteristics that have been monitored continuously are suspended solids, pH, conductance, temperature, density, dissolved oxygen, and chlorine residual. Complete chemical analyses are frequently made on a periodic basis on composite or grab samples. Because bacteria may have a damaging effect on reservoir permeability, periodic biological analysis of some wastewaters may be desirable to insure that organisms are not being introduced.

Injection pressure is monitored to provide a record of reservoir performance and as evidence of compliance with regulatory restrictions. Injection pressures are limited to prevent hydraulic fracturing of the injection reservoir and confining beds, or damage to well facilities. As with flow data, injection pressure should be continuously recorded.

Pressure fall-off data collected after any extended period of continuous operation can be used to check the performance of the reservoir as compared with is original condition. However, it should be noted that the

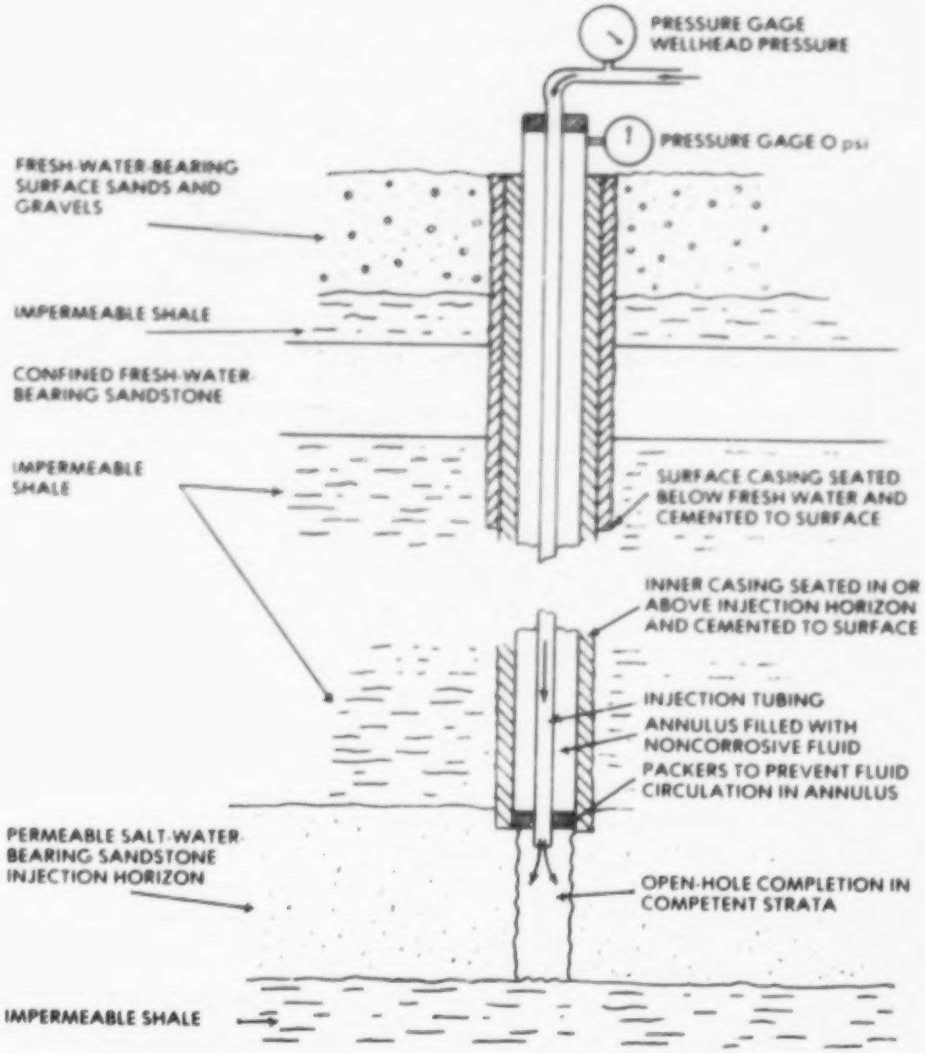
PRESSURE GAGE
WELLHEAD PRESSURE
PRESSURE GAGE O psi
FRESH-WATER-BEARING SURFACE SANDS AND GRAVELS
IMPERMEABLE SHALE
CONFINED FRESH-WATER-BEARING SANDSTONE
IMPERMEABLE SHALE
SURFACE CASING SEATED BELOW FRESH WATER AND CEMENTED TO SURFACE
INNER CASING SEATED IN OR ABOVE INJECTION HORIZON AND CEMENTED TO SURFACE
INJECTION TUBING
ANNULUS FILLED WITH NONCORROSIVE FLUID
PACKERS TO PREVENT FLUID CIRCULATION IN ANNULUS
PERMEABLE SALT-WATER-BEARING SANDSTONE INJECTION HORIZON
OPEN-HOLE COMPLETION IN COMPETENT STRATA
IMPERMEABLE SHALE

Figure 37. Schematic diagram of an industrial waste injection well completed in competent sandstone (modified after Warner, 1965).

time scale of continuous recorders is not generally adequate for providing data during the early period of a pressure fall-off test, so the continuously recorded data will probably need to be supplemented with additional observations in order to have a complete record of the test.

Figure 28 (page 50) is an example of the pressure response that would ideally be expected during a period of continuous injection. Pressure increase through time should be linear on a semilogarithmic scale, after an early period of adjustment.

In contrast with this ideal behavior, Figure 38 shows the injection pressure history of a wastewater injection well completed in a carbonate reservoir. Two marked periods of pressure decline are shown, one in 1967-1968 and one in 1970. The explanation for this is believed to be that the wastewater being injected, initially an acid solution, reacted with the carbonate reservoir to increase the permeability and thus decrease the injection pressure. The period of gradual pressure increase during 1969-1970 is probably the normal buildup following this initial period of permeability increase. In 1970, the wastewater composition was changed to include a second acid stream. This new stream apparently caused additional permeability increase and a temporary reduction in injection pressure, after which the expected pressure buildup resumed.

Figure 39 shows the plots of two pressure fall-off tests performed in an injection well of the Monsanto Company, Pensacola, Florida. This well is also constructed in a carbonate aquifer. One test was made in

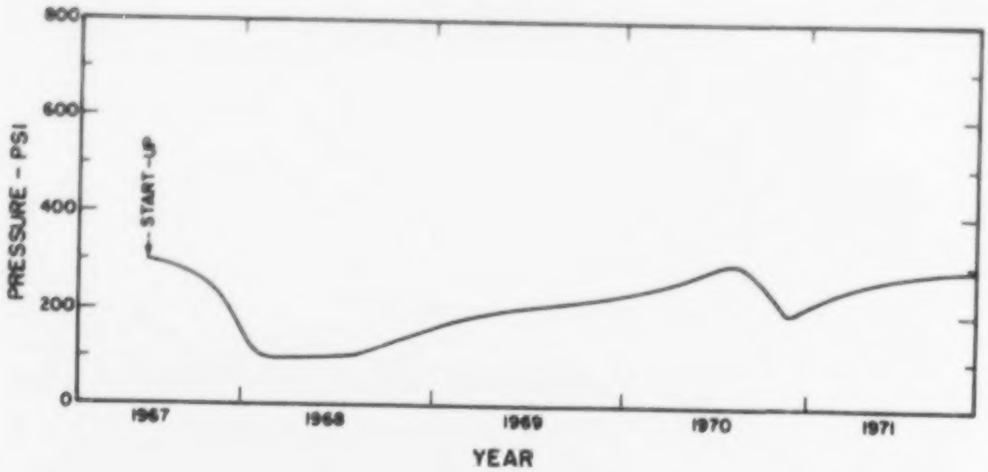

Figure 38. Pressure history of a well injecting into a carbonate aquifer.

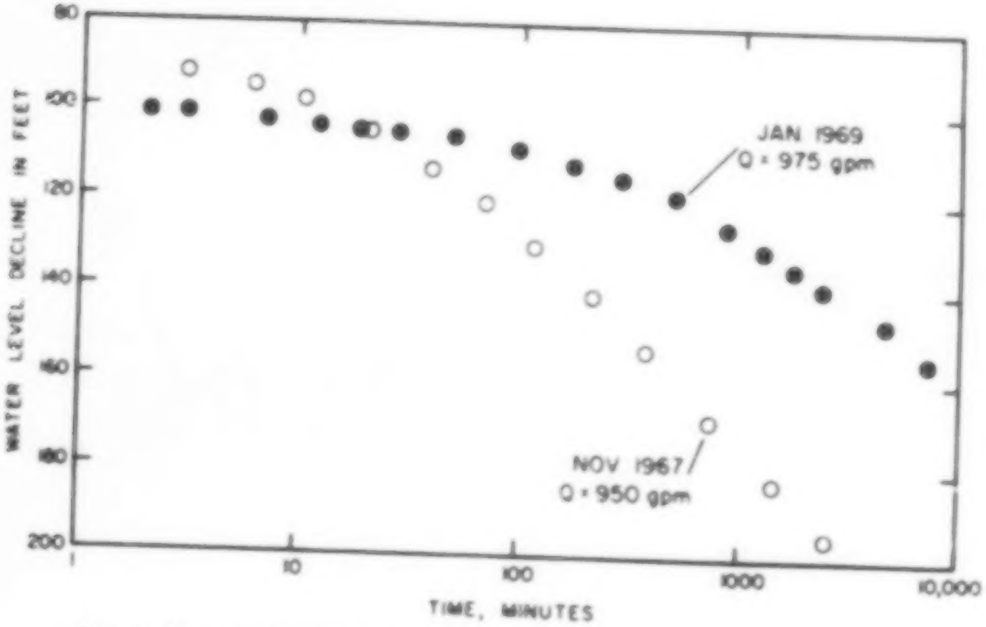

Figure 39. Semilogarithmic plot of two pressure fall-off tests measured in an injection well of the *Monsanto Company*, Pensacola, Florida (Goolsby, 1971).

November 1967, before injection of an acidic wastewater stream began. The other test was performed in January 1969, after the acidic wastewater had been injected for nine months. The second test shows a much slower rate of fall-off, indicating an increased permeability in the vicinity of the well bore caused by reaction of the acidic wastewater with the carbonate aquifer. This conclusion is substantiated by an increase in the injection index for this and another well during the same time period, as shown in Figure 40.

Some other possible causes of deviation from the ideal response are the presence of hydrologic barriers of conduits, leaky confining beds, and permeability reduction from suspended solids, chemical reactions, etc. The variety of factors that may influence well behavior indicates the need for maintaining an accurate, detailed well history so that the probable cause of any unusual performance can be deduced and the appropriate action taken.

Pressure in the casing-tubing annulus is monitored to detect any changes that might indicate leakage through the injection tubing or the tubing-casing packer. When a packer is used, the casing-tubing annulus pressure should be zero, except perhaps for some pressure resulting from expansion of

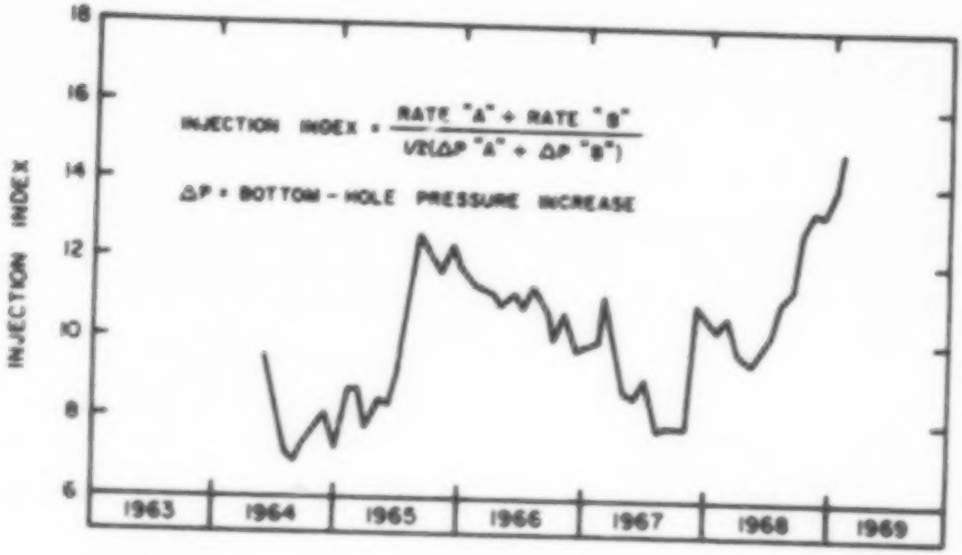

Figure 40. *Monthly average injection index of two injection wells of the Monsanto Company, Pensacola, Florida (Goolsby, 1971).*

the injection tubing. In cases where a packer is not used, pressure will be exerted directly on the fluid in the annulus, and indication of leakage would be a significant change in the annulus pressure.

Other methods of monitoring of the injection well also deserve mention. The corrosion rate of well tubing and casing may be monitored by use of corrosion coupons inserted in the well. A conductivity probe may be used to detect a change in the chemistry of the fluid in the casing-tubing annulus. In wells with packers the conductivity probe can be used to detect tubing leaks, and in wells without tubing to detect shifts in the interface between the injected fluid and the casing-tubing fluid. Another technique that has been used to monitor the casing-tubing annulus is continuous cycling of the annulus fluid and analysis of the return flow for evidence of contamination by wastewater.

PERIODIC INSPECTION AND TESTING

Sufficient incidents have occurred in the past to emphasize the need for periodically inspecting or testing the subsurface facilities of injection wells, particularly when chemically reactive wastes are being injected. One such incident was the rather spectacular failure of a wastewater injection well at the Hammermill Paper Mill, Erie, Pennsylvania. In that instance, the well casing parted as a result of corrosion and a portion of it was reportedly lifted from the hole by fluid pressure. Substantial loss of wastewater into Lake Erie and abandonment of the well resulted. Other cases have been reported in which portions of tubing or casing have failed by corrosion and caused temporary or permanent shutdown of the well. There may also be reason to examine the well bore to check for the location of zones of wastewater entrance, enlargement due to chemical reaction, the location and orientation of induced fractures, buildup or precipitates or filtered solids, etc. Examples are available of wells that have been abandoned or modified because of borehole enlargement that led to collapse of the borehole or damage to the casing or cement near the bottom of the casing string.

Methods of inspection of casing, tubing, cement and the well bore are:

- Pulling of tubing and visual or instrumental inspection
- Inspection of casing or tubing in place, using magnetic logs
- Inspection of casing, tubing, or the well bore with caliper or televiewer logs
- Pressure testing of casing
- Inspection of casing cement with cement bond logs
- Inspection of casing, cement, or the well bore with injectivity or temperature profiles or other appropriate logs.

The process of pulling and inspecting tubing is self-explanatory. Mechanical methods are available, for example, for inspection of lined steel tubing for flaws in the lining. Individual joints of tubing can be pressure tested at the surface for leakage.

Magnetic down-hole casing or tubing inspection services are provided by oil field service companies. These logs indicate, by virtue of the electromagnetic response of steel pipe, the relative pipe thickness. Thin areas may indicate corrosion or other damage. If such a log is run early in the life of the pipe, then logs run after the well has been in operation are much more easily interpreted. Figure 41 shows the response of a pipe inspection log and photographs of the casing that was pulled after running the log. Figure 42 is a portion of a pipe inspection log from a wastewater injection well which indicates possible corrosion in the interval from 1480 to 1510 feet; regular deflections on the log represent casing joints. Corrosion could either be on the inside or the outside of the casing.

Caliper logs provide a record of the inside diameter of pipe or borehole walls and may show intervals of pipe corrosion, borehole enlargement, or borehole plugging at the formation face. Figure 43 shows

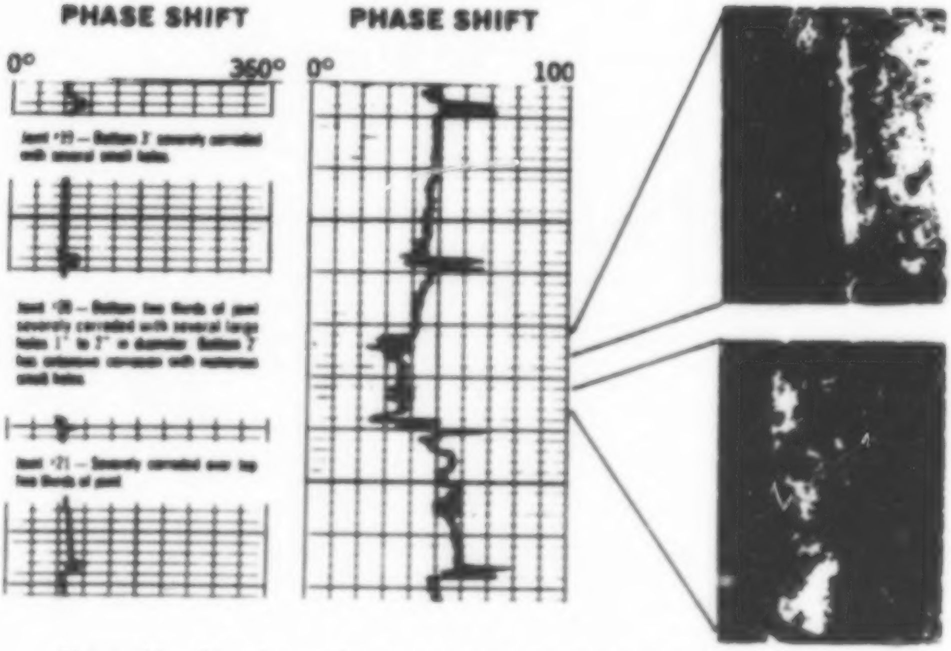

Figure 41. Pipe Inspection Log and photographs of casing pulled after log was run to verify the log (Schlumberger, 1970).

portions of a caliper log run before injection and after 5 years of injection of an acidic wastewater into a limestone aquifer. The log indicates considerable borehole enlargement as a result of dissolution of the limestone by the injected acidic waste in the interval from 1500 to 1600 feet. It would be reasonable to conclude that most of the wastewater entered that interval.

Borehole televiewers provide an image of the pipe of borehole wall as produced by the reflection of sound waves emitted from a sonde. The combination sound source and receiver is highly directional and is rotated rapidly as the tool is moved up the hole. Thus, the hole is continuously scanned. The resulting information is displayed on an oscilloscope and a film made of the scope display. The picture obtained depicts the well bore as though it were split open and laid out for inspection. Figure 44 illustrates the detail with which the borehole televiewer can indicate casing damage. In Figure 45 vertical fractures in the borehole wall of a well in Oklahoma are shown.

Pressure testing can be used to detect casing leaks and it is required by law in many oil-producing States as a method of testing the integrity of casing in new wells at the time that the casing is cemented into the borehole. In such tests, a cement plug is left at the bottom of the casing during cementing and allowed to harden. The interior of the casing

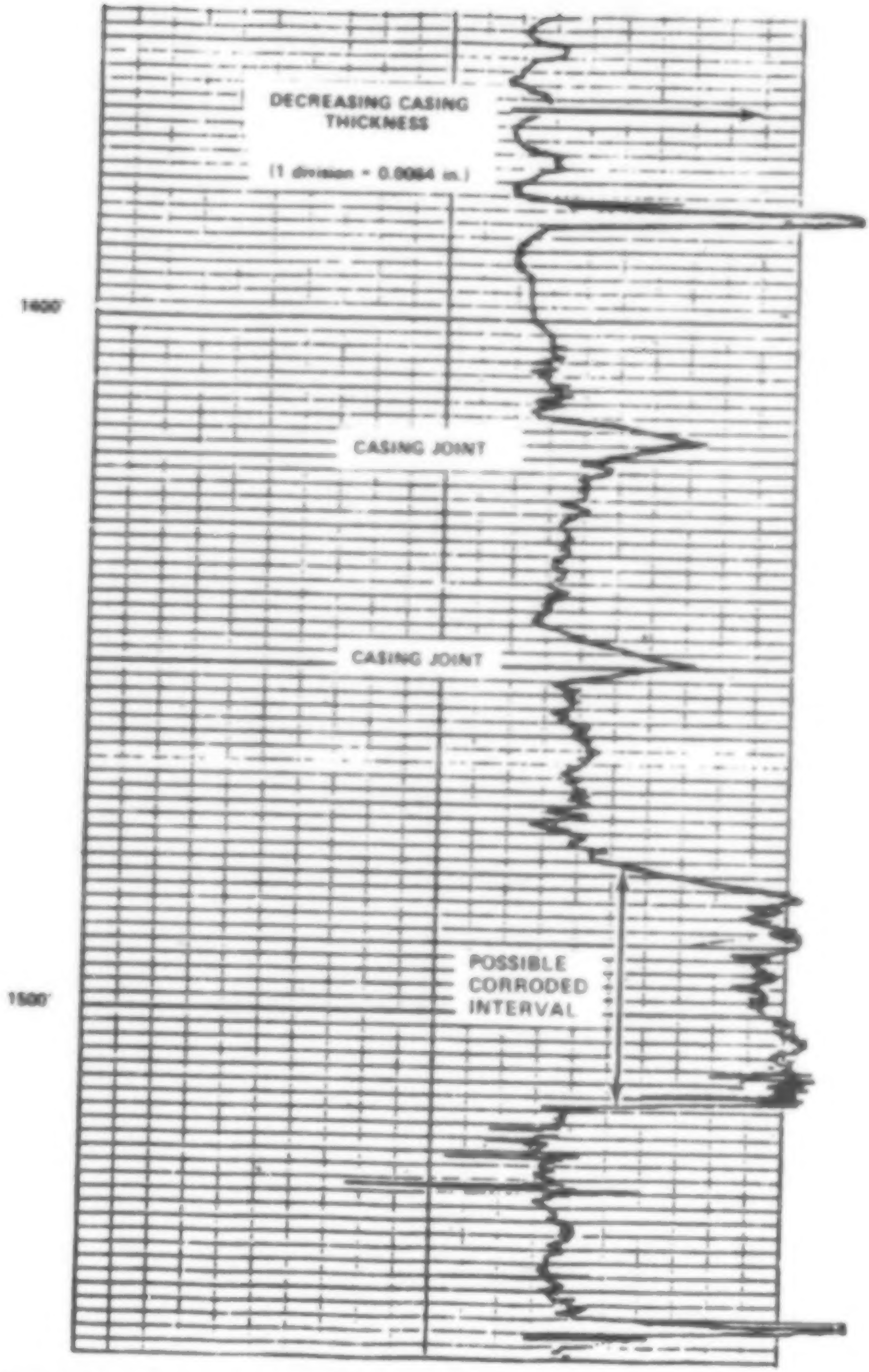

Figure 42. Portion of a casing inspection log run in a wastewater injection well showing possible corrosion in the interval from 1480 to 1510 feet.

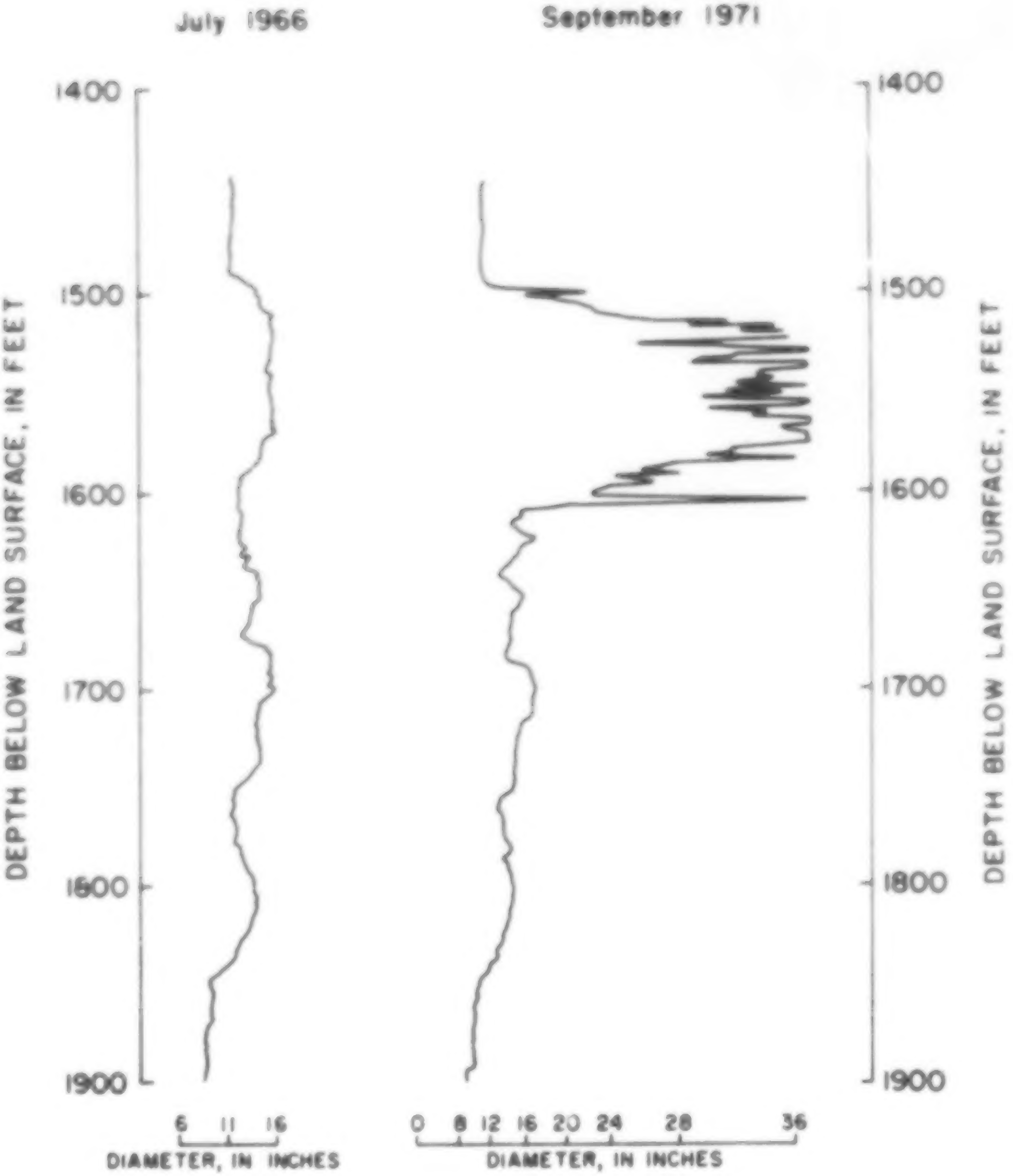

Figure 43. Preinjection and postinjection caliper logs from a wastewater injection well at Belle Glade, Florida, showing solution of the limestone aquifer in the 1500- to 1600-ft interval by acidic wastewater (Black, Crow, and Eidsness, 1972).

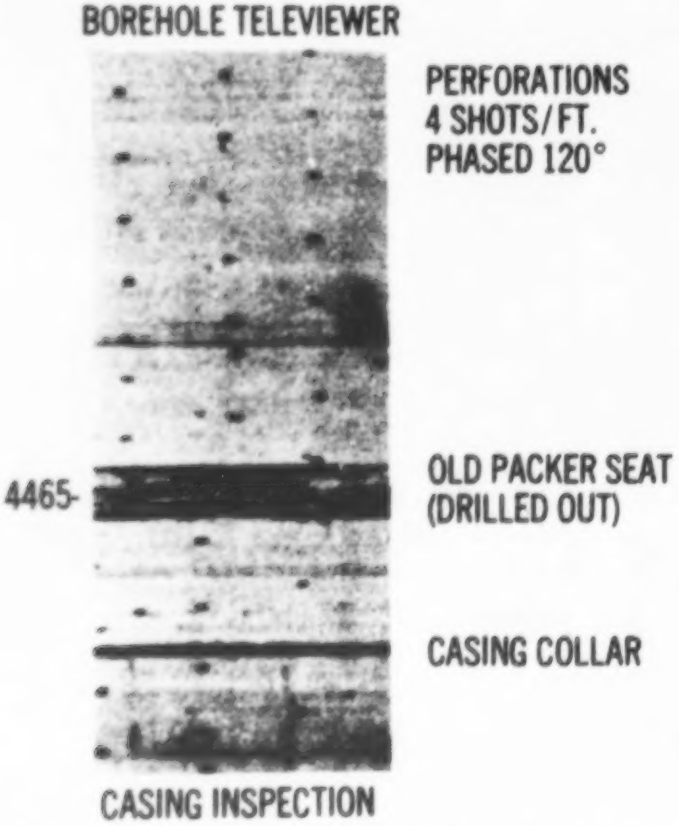

Figure 44. Borehole televiewer log of a section of casing showing casing perforations, packer seat, and casing collar (Schlumberger, 1970).

is then subjected to a specified amount of fluid pressure (0.2 psi per foot of casing in Texas).* Rapid decline in pressure indicates leakage from the casing. Such a test could also be performed periodically in operating wells by setting temporary plugs or using packers.

The cement-bond log is used to determine the quality of the casing-cement bonding and to detect channels in the cement behind the casing, or to detect damage to cement from high-pressure injection of chemical reaction. The cement-bond log is a continuous measurement of the amplitude of elastic waves after they have traveled through a short length of pipe, cement, and perhaps formation (Figure 46). The amplitude of the elastic wave is maximum in uncemented casing and will generally be lower as the degree of bonding and integrity of the cement improves.

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*Texas Railroad Commission rules.

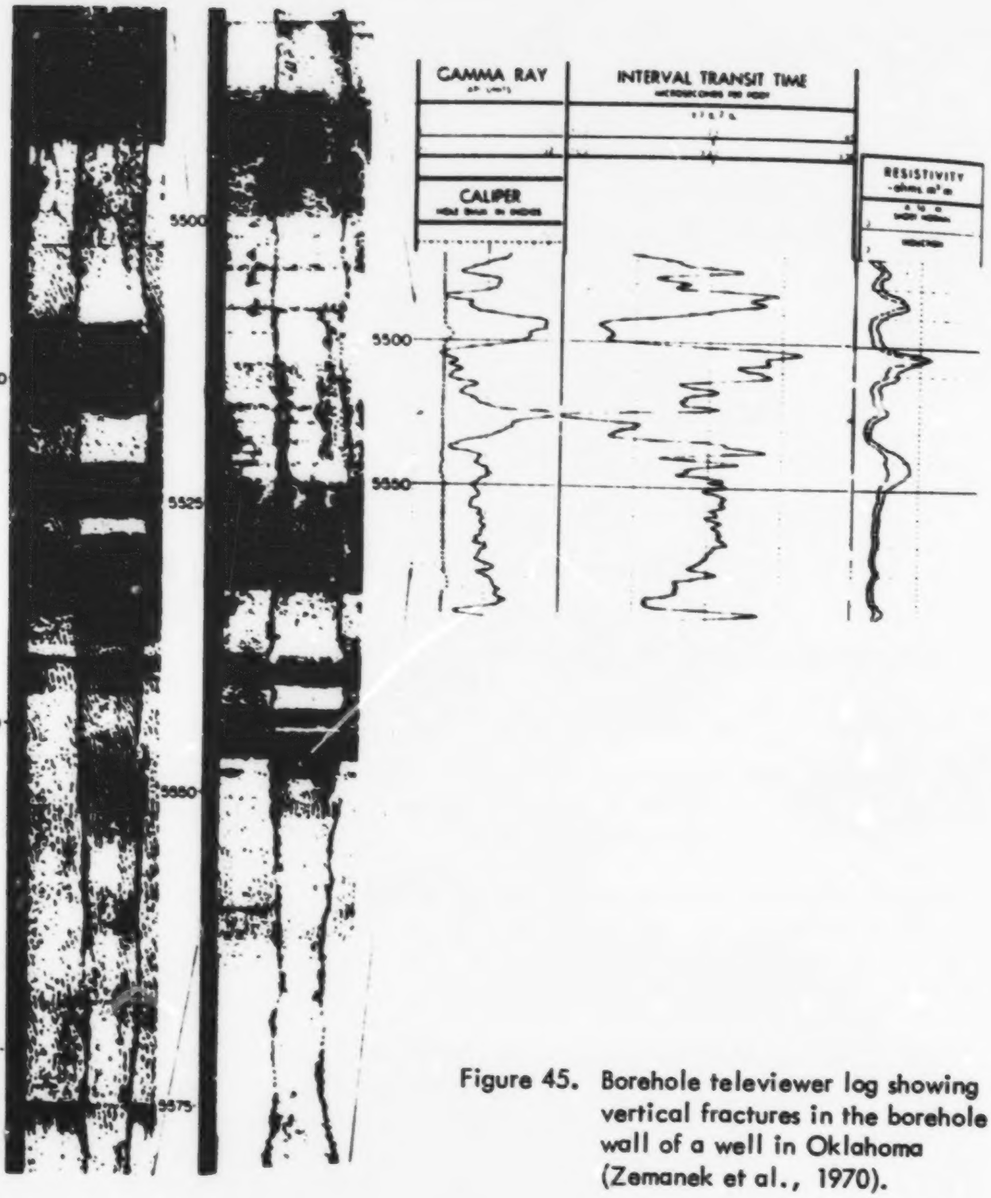

Figure 45. Borehole televiewer log showing vertical fractures in the borehole wall of a well in Oklahoma (Zemanek et al., 1970).

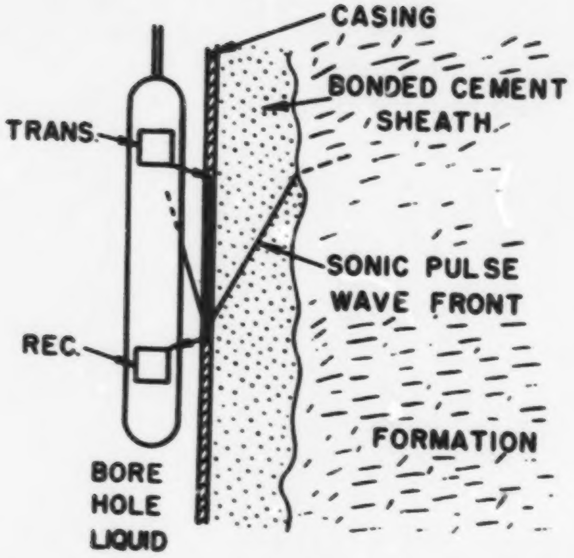

Figure 46. Schematic diagram of a cement bond logging tool in a borehole (Grosmangin et al., 1960).

Thus, the relative amplitudes of the waves in different portions of a well can be interpreted to indicate the condition of the cement and degree of bonding. Complications that occur in the interpretation of cement-bond logs are discussed be Fertl et al. (1974). Figure 47 shows portions of a cement-bond log from an acid wastewater injection well. It appears that the casing in the vicinity of 1900 to 2000 feet is not bonded. The interval from 2700 to 2800 feet, near the base of the casing, shows progressively better bonding between the casing and cement.

Some other possible inspection methods are radioactive tracer injectivity profiles, flow-meter injectivity profiles, and temperature profiles. The objective of these methods is to determine where injected fluid is going. Radioactive tracer injectivity profiles accomplish this through injection of a radioactive tracer and logging of the borehole with a gamma ray detector. The detector measures concentrations of tracer, which indicate paths of tracer flow. Flow-meter injectivity profiles are similar, except that flow paths of injected fluid are indicated by a flow meter rather than by an injected tracer. Temperature profiles may indicate anomalies at points where injected fluids enter the receiving formation or where they escape through casing or tubing leaks. Such anomalies would obviously be most likely to be detectable in wells where significant temperature contrasts exist between injected fluids and the aquifers.

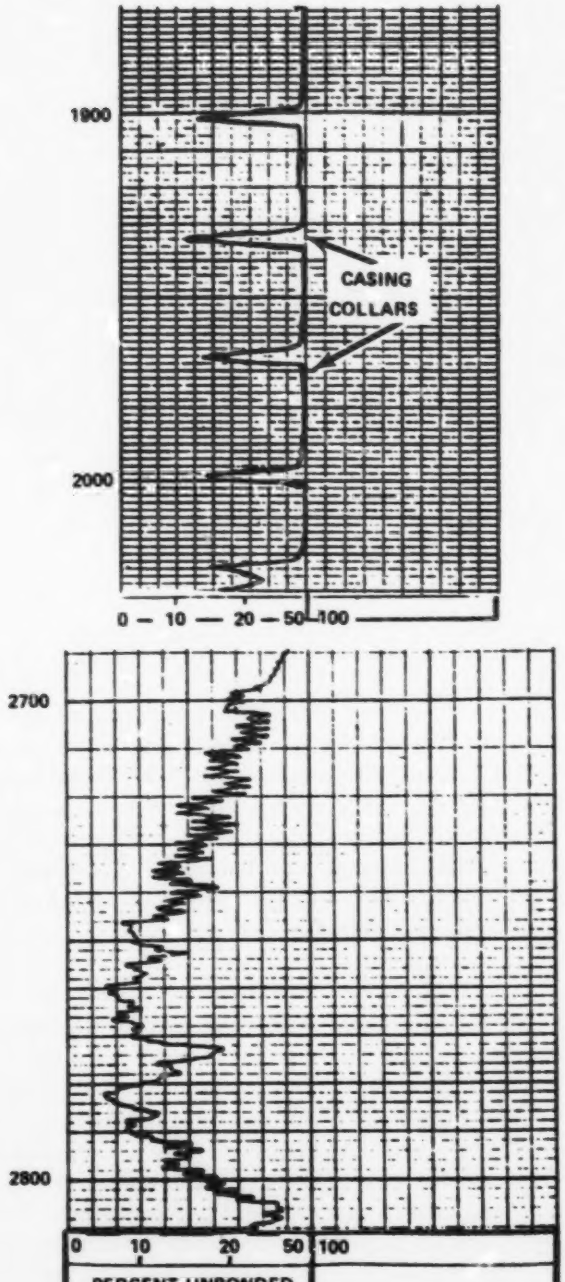

Figure 47. Portions of a cement-bond log from an acid wastewater injection well.

Repetitive running of resistivity or radioactive logs may also be used to locate the zones that are accepting injected wastewater. Resistivity logs are limited to the uncased portion of a well, but radioactive logs have been used to locate a freshwater-saline water interface behind casing (Keys and MacCary, 1973).

MONITORING WELLS

The subject of monitoring wells has been a controversial one in regulation of wastewater injection. Such wells are routinely used in shallow groundwater studies but are less frequently used in conjunction with wastewater injection, for reasons that will be examined.

At least three hydrogeologically different types of monitor wells can be and have been constructed, each with different objectives as shown below:

Well Type	Objective
1. Constructed in receiving aquifer—nondischarging	A. Obtain geologic data
	B. Monitor pressure in receiving aquifer
	C. Determine rate and direction of wastewater movement
	D. Detect geochemical changes in injected wastewater
	E. Detect shifts in freshwater-saline water interfaces
2. Constructed in or just above confining unit —nondischarging	A. Obtain geologic data
	B. Detect leakage through confining unit
3. Constructed in a freshwater aquifer above receiving aquifer	A. Obtain geologic data
	B. Detect evidence of freshwater contamination

Monitor wells constructed in the receiving aquifer are normally nondischarging because a discharging well would defeat most of the purposes of this type of monitor well. Also, the produced brines would have to be disposed of. Although it is not normally necessary to monitor pressure in the receiving aquifer except at the injection well, special monitor wells may be desired where pressure at a distance from the injection well is of concern because of the presence of known or suspected faults or abandoned wells that may be inadequately plugged. The pressure response in a monitor well at such locations would indicate the extent of danger of flow through such breaches in the confining beds and possibly also indicate whether leakage was occurring.

Constructing a monitor well or wells in the receiving aquifer is the only direct means of verifying the rate and direction of wastewater movement. More than one well will frequently be necessary to meet this objective, because monitor wells of this type only sample wastewater plumes that pass directly through the well bore; and nonuniformity in aquifer porosity and permeability can cause the wastewater to arrive very rapidly or perhaps not at all at a particular well. A single well might be satisfactory where aquifer and fluid properties are such that it is judged most likely that wastewater movement will be radial and reasonably uniform or where the objective is to detect wastewater arrival at a particular point of interest. These same comments apply to wells intended to detect geochemical changes in injected wastewater. A difference is that a well for monitoring geochemical changes would be placed near enough to the injection well so that the wastewater front will arrive within a relatively short time, whereas, a well for detecting wastewater arrival at a point of concern might be beyond the expected ultimate travel distance of the wastewater.

A well intended to detect a shift in a freshwater-saline water interface should be located either within that interface or in the freshwater portion of the aquifer just beyond the interface. Because movement of this interface will be in response to increased aquifer fluid pressure, rather than to actual displacement by the wastewater front, detection of its movement should be possible with a small number of observation wells, perhaps even a single properly located one. It is possible to estimate rates of movement for a particular case and to determine if a monitor well is likely to be able to detect such a shift. Monitoring would be for confirmation of the calculations and to allow for revisions in regulation if unexpected results occur.

Negative factors should be considered in any case where deep monitor wells are contemplated: monitor wells in the receiving aquifer may be of limited usefulness, and they provide an additional means by which injected wastewater could escape from the receiving aquifer. In a number of cases, multiple injection wells have been constructed at a site, one or more of which may be standby injection wells. Standby wells can be used for monitoring of aquifer pressure, and for sampling of aquifer water. However, if they have been operated or even extensively tested, their use for monitoring may be impaired.

Some examples of the use of observation wells in the receiving aquifer are given by Goolsby (1971 and 1972), Kaufman et al. (1973), Leenheer and Malcom (1973), Peek and Heath (1973), and Hanby and Kidd (1973).

For detection of leakage, the principal of using nondischarging monitor wells completed in the confining beds or in a confined aquifer immediately above the confining beds has been widely discussed but has been little used. This type of well has the potential for acting as a very sensitive indicator of leakage by allowing measurement of small changes in pressure (or water level) that accompany leakage. A well of this type is best suited for use where the confining unit is relatively thin and well defined and where the engineering properties of the two aquifers are within a range such that pressure response in the monitored aquifer will be rapid if leakage occurs. Use of the concepts outlined by Witherspoon and Neuman (1972) will allow evaluation of the possibilities of success of this monitoring method in a specific situation. In many actual cases, confining beds are several hundred to several thousand feet thick and do not contain aquifers suitable for such monitoring. In other cases, the physical circumstances are amenable to such monitoring but several thousands of feet of interbedded aquitards and saline water aquifers are present; in these cases, slow vertical leakage across the aquitard immediately over the injection interval is not significant because it can be predicted that there will be no measurable influence at the stratigraphic level where freshwater or other resources occur.

Two good examples of the usefulness of monitoring an aquifer immediately above the confining beds are provided by Kaufman et al. (1973) and Leenheer and Malcolm (1973). In the case described by Kaufman et al., wastewater leakage from the lower Floridan aquifer through 150 feet of confining beds into the upper Floridan aquifer was detected by geochemical analysis of water from a monitor well constructed in the upper Floridan aquifer. No pressure effects were noticed in this instance. Leenheer and Malcolm summarized a case history in which leakage through the confining beds was detected first by pressure increase in an overlying aquifer, and later confirmed by chemical analysis which showed wastewater contamination of water in the aquifer.

The type of monitor well most commonly in use is that which is completed in a freshwater aquifer above the injection horizon for detecting freshwater contamination. In a number of locations, this type of monitoring is provided by wells that are a part of the plant's water supply system. In other cases, the wells have been constructed particularly for monitoring and are not used for water supply. Wells for detection of freshwater contamination should be discharging wells because they then sample an area of aquifer within their cone of depression. As previously mentioned, nondischarging wells are of limited value for detection of contamination because they sample only that water that passes through the well bore. Wells for monitoring freshwater contamination should be located close to the anticipated sources of contamination, which are:

SURVEILLANCE OF OPERATING WELLS

- The injection well itself
- Other nearby deep wells, active or abandoned
- Nearby faults or fracture zones.

No example is known to the writer where monitor wells of this type have detected wastewater contamination of a water supply aquifer.

In the preceding discussion, it has been implied that separate wells would need to be constructed for surveillance of aquifers and aquicludes at different depths. This is not necessarily the case. Talbot (1972) shows how the injection well itself can be adapted for monitoring of overlying aquifers, and also how monitor wells may be constructed for surveillance of more than one aquifer. Wilson et al. (1973) describe a case where the injection well was modified as shown in Figure 48 for monitoring of two aquifers overlying the injection zone.

Since the objectives for each of the types of monitoring wells discussed are worthwhile ones, why are monitor wells not more widely used? The answer to this question is that the potential benefits are often judged to be small in comparison with the costs and negative aspects. Therefore, such wells may not be voluntarily constructed by the operating companies nor required by the regulatory agencies. In particular, monitor wells constructed in the receiving aquifer are often difficult to justify because such wells are the most expensive form of surveillance and may yield very little information that is important for regulation. It can reasonably be concluded that monitor wells should not be arbitrarily required, but should be used where the local circumstances justify them.

OTHER MONITORING METHODS

A method of monitoring not so far mentioned is the sampling of springs, streams, or lakes that could be affected by injection. There are few instances where such monitoring would be applicable; but, for example, where springs originate along a fault within the area of pressure influence of the injection well an increase in discharge rate or change in water quality could be an indication of leakage of formation water along the fault in response to the increased pressure from injection. Also, springs and gaining streams act similarly to discharging wells in that they provide a composite sample of groundwater over their area of influence; thus, they might reveal leakage from unknown fracture zones or abandoned wells that connect a shallow groundwater aquifer with the injection interval. In a similar way, lakes may be collecting points for groundwater seepage or streams and may reflect quality changes in shallow groundwater aquifers.

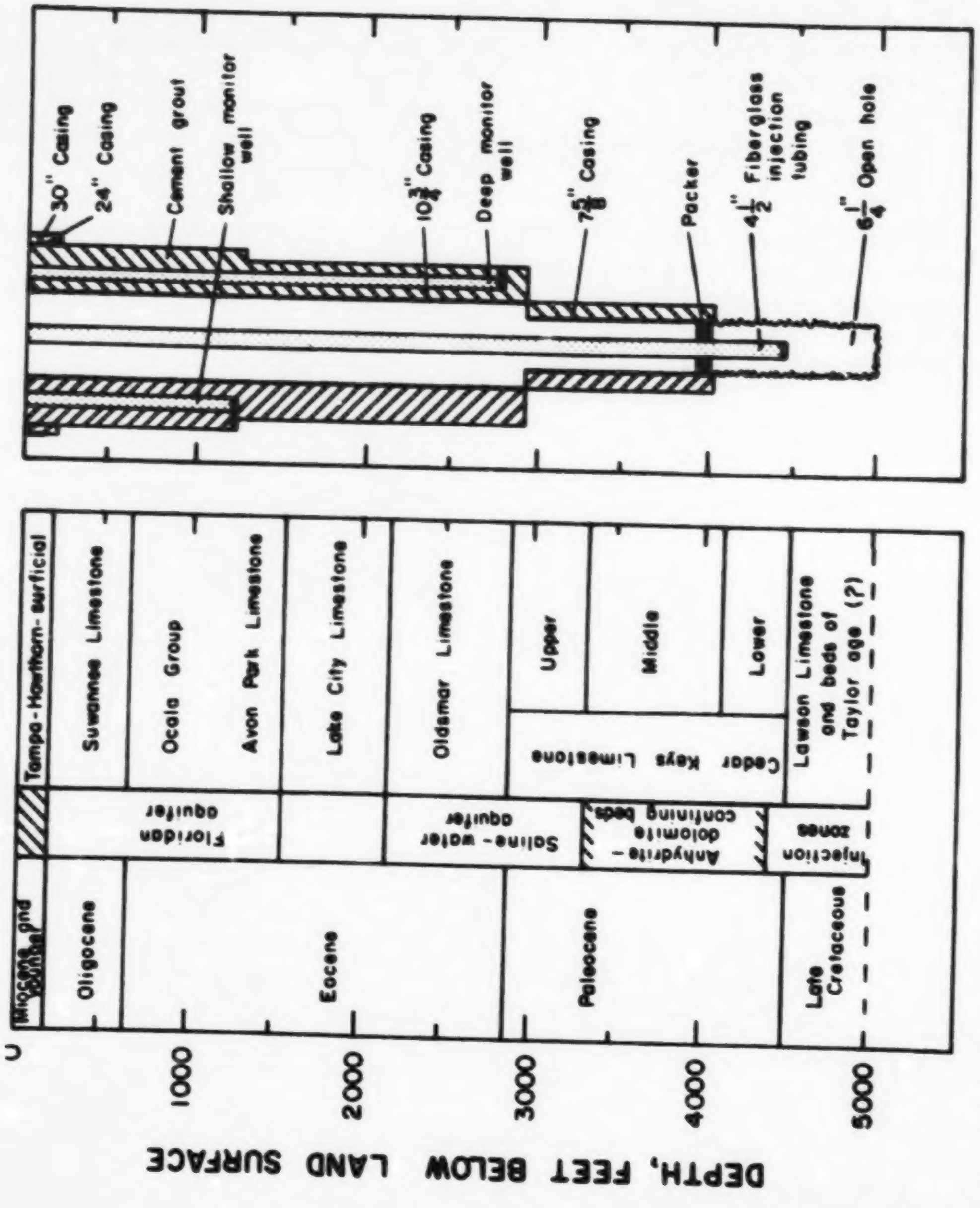
DEPTH, FEET BELOW LAND SURFACE
0
1000
2000
3000
4000
5000
Miocene and younger
Oligocene
Eocene
Paleocene
Late Cretaceous
Floridan aquifer
Saline - water aquifer
Anhydrite - dolomite confining beds
Injection zones
Tampa - Hawthorn - surficial
Suwannee Limestone
Ocala Group
Avon Park Limestone
Lake City Limestone
Oldsmar Limestone
Cedar Keys Limestone
Upper
Middle
Lower
Lawson Limestone and beds of Taylor age (?)
30" Casing
24" Casing
Cement grout
Shallow monitor well
10 3/4" Casing
Deep monitor well
7 5/8" Casing
Packer
4 1/2" Fiberglass injection tubing
6 1/4" Open hole

Figure 48. Geologic column and construction of a wastewater injection well at Mulberry, Florida, where two aquifers above the injection zone are monitored through the injection well (Wilson et al., 1973).

Surface geophysical methods offer some limited possibilities for monitoring of wastewater injection. Barr (1973) discussed the feasibility of monitoring the distribution of injected wastewater with seismic reflection. Monitoring by seismic reflection depends on the existence of a sufficient density contrast between injected and interstitial water, and no field trials of monitoring by seismic reflection have been reported. Electrical resistivity surveying could be useful for monitoring the movement of freshwater-saline water interfaces or for detecting saline water pollution of freshwater aquifers (Swartz, 1937; Warner, 1969).

Monitoring for earthquake occurrence is accomplished by use of a network of seismometers placed in the vicinity of the injection well and in the vicinity of nearby faults along which seismic events might be triggered. Examples of this form of monitoring are described by Raleigh (1972) and by Hanby and Kidd (1973). In a case where earthquake stimulation is considered a possibility, seismic monitoring should begin before the well is operated to obtain background data.

SECTION VIII

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APPENDIX

EPA POSITION ON SUBSURFACE EMPLACEMENT OF FLUIDS

The material in this appendix is reproduced from the Federal Register of April 9, 1972, pp 12922-12933. (See also Hall and Ballentine, 1973)

INTRODUCTORY COMMENTS

The Environmental Protection Agency, in concert with the objectives of the Federal Water Pollution Control Act, as amended (33 U.S.C. 1251 et seq.; 86 Stat. 816 et seq.; Pub. L. 92-500) " . . . to restore and maintain the chemical, physical, and biological integrity of the Nation's water" has established an EPA policy on Subsurface Emplacement of Fluids by Well Injection" which was issued internally as Administrator's Decision Statement No. 5. The purpose of the policy is to establish the Agency's concern with this technique for use in fluid storage and disposal and its position of considering such fluid emplacement only where it is demonstrated to be the most environmentally acceptable available method of handling fluid storage or disposal. Publication of the Policy as information establishes the Agency's position and provides guidance to other Federal Agencies, the States, and other interested parties.

Accompanying the policy statement are "Recommended Data Requirements for Environmental Evaluation of Subsurface Emplacement of Fluids by Well injection well system; and to insure ments is to provide guidance for potential injectors and regulatory agencies concerning the kinds of information required to evaluate the prospective injections well system; and to insure protection of the environment. The Recommended Data Requirements require sufficient information to evaluate complex injection operations for hazardous materials, but may be modified in scope by a regulatory agency for other types of injection operations.

The EPA recognises that for certain industries and in certain locations the disposal of wastes and the storage of fluids in the subsurface by use of well injection may be the most environmentally acceptable practice available. However, adherence to the policy requires the potential injector to clearly demonstrate acceptability by the provision of technical analyses and data justifying the proposal. Such demonstration requires conventional engineering and other analyses which indicate beyond a reasonable doubt the efficacy of the proposed injection well operation.

Several issues within the policy should be highlighted and explained to avoid confusion. One of the goals of the policy is to protect the integrity of the subsurface environment. In the context of the policy statement, integrity means the prevention of unplanned fracturing or other physical impairment of the geologic formations and the avoidance of undesirable changes in aquifers, mineral deposits or other resources. It is recognised that fluid emplacement by well injection may cause some change in the environment and, to some extent, may preempt other uses.

Emplacement is intended to include both disposal and storage. The difference between the two terms is that storage implies the existence of a plan for recovery of the material within a reasonable time whereas disposal implies that no recovery of the material is planned at a given site. Either operation would require essentially the same type of information prior to injection. However, the attitude of the appropriate regulatory agency toward evaluation of the proposals would be different for each type operation. The EPA policy recognises the need for injection wells in certain oil and mineral extraction and fluid storage operations but requires sufficient environmental safeguards to protect other uses of the subsurface, both during the actual injection operation and after the injection has ceased.

The policy considers waste disposal by well injection to be a temporary means of disposal in the sense that it is approved only for the life of an issued permit. Should more environmentally acceptable disposal technology become available, a change to such technology would be required. The term "temporary" is not intended to imply subsequent recovery of injected waste for processing by another technology.

Paragraph 5 of the policy and program guidance provides that EPA will apply the policy to the extent of its authorities in conducting all EPA program activities. The applicability of the policy to participation by the several States in the NPDES permit program under section 402 of the Federal Water Pollution Control Act as amended has been established previously by § 124.80(d) of Part 124 entitled "State Program Elements Necessary for Participation in the National Pollutant Discharge Elimination System," 37 FR 28390 (December 22, 1972). These guidelines provide that each EPA Regional Administrator must distribute the policy to the Director of a State water discharge permit issuing agency, and must utilize the policy in his own review of any permits for disposal of pollutants into wells that are proposed to be issued by States participating in the NPDES.

Dated: April 2, 1974.

John Quarles,
Acting Administrator.

ADMINISTRATOR'S DECISION STATEMENT NO. 5 EPA POLICY ON SUBSURFACE EMPLACEMENT OF FLUIDS BY WELL INJECTION

This ADS records the EPA's position on injection wells and subsurface emplacement of fluids by well injection, and supersedes the Federal Water Quality Administration's order COM 5040.10 of October 15, 1970.

Goals. The EPA Policy on Subsurface Emplacement of Fluids by Well Injection is designed to:

(1) Protect the subsurface from pollution or other environmental hazards attributable to improper injection or ill-sited injection wells.

(2) Ensure that engineering and geological safeguards adequate to protect the integrity of the subsurface environment are adhered to in the preliminary investigation, design, construction, operation, monitoring and abandonment phases of injection well projects.

(3) Encourage development of alternative means of disposal which afford greater environmental protection.

Principal findings and policy rationale. The available evidence concerning injection wells and subsurface emplacement of fluids indicates that:

(1) The emplacement of fluids by subsurface injection often is considered by government and private agencies as an attractive mechanism for final disposal or storage owing to: (a) the diminishing capabilities of surface waters to receive effluents without violation of quality standards, and (b) the apparent lower costs of this method [illegible] disposal or storage over conventiona[illegible] advanced waste management techniques. Subsurface storage capacity is a natural resource of considerable value and like any other natural resource its use must be conserved for maximal benefits to all people.

(2) Improper injection of municipal or industrial wastes or injection of other fluids for storage or disposal to the subsurface environment could result in serious pollution of water supplies or other environmental hazards.

(3) The effects of subsurface injection and the fate of injected materials are uncertain with today's knowledge and could result in serious pollution or environmental damage requiring complex and costly solutions on a long-term basis.

Policy and program guidance. To ensure accomplishment of the subsurface protection goals established above it is the policy of the Environmental Protection Agency that:

(1) The EPA will oppose emplacement of materials by subsurface injection without strict controls and a clear demonstration that such emplacement will not interfere with present or potential use of the subsurface environment, contaminate ground water resources or otherwise damage the environment.

(2) All proposals for subsurface injection should be critically evaluated to determine that:

(a) All reasonable alternative measures have been explored and found less satisfactory in terms of environmental protection;

(b) Adequate preinjection tests have been made for predicting the fate of materials injected;

(c) There is conclusive technical evidence to demonstrate that such injection will not interfere with present or potential use of water resources nor result in other environmental hazards;

(d) The subsurface injection system has been designed and constructed to provide maximal environmental protection;

(e) Provisions have been made for monitoring both the injection operation and the resulting effects on the environment;

(f) Contingency plans that will obviate any environmental degradation have been prepared to cope with all well shut-ins or any well failures;

(g) Provision will be made for supervised plugging of injection wells when abandoned and for monitoring to ensure continuing environmental protection.

(3) Where subsurface injection is practiced for waste disposal, it will be recognized as a temporary means of disposal until new technology becomes available enabling more assured environmental protection.

(4) Where subsurface injection is practiced for underground storage or for recycling of natural fluids, it will be recognized that such practice will cease or be modified when a hazard to natural resources or the environment appears imminent.

(5) The EPA will apply this policy to the extent of its authorities in conducting all program activities, including regulatory activities, research and development, technical assistance to the States, and the administration of the construction grants, State program grants, and basin planning grants programs and control of pollution at Federal facilities in accordance with Executive Order 11752.

William D. Ruckelshaus,
Administrator.

February 6, 1973.

RECOMMENDED DATA REQUIREMENTS FOR ENVIRONMENTAL EVALUATION OF SUBSURFACE EMPLACEMENT OF FLUIDS BY WELL INJECTION

The Administrator's Decision Statement No. 5 on subsurface employment of fluids by well injection has been prepared to establish the Agency's position on the use of this disposal and storage technique. To aid in implementation of the policy a recommended data base for environmental evaluation has been developed.

The following parameters describe the information which should be provided by the injector and are designed to provide regulatory agencies sufficient information to evaluate the environmental acceptability of any proposed well injection. A potential injector should initially contact the regulatory authority to determine the preliminary investigative and data requirements for a particular injection well as these may vary for different kinds of injection operations. The appropriate regulatory authority will specify the exact data requirements on a case by case basis.

(a) An accurate plat showing location and surface elevation of proposed injection well site, surface features, property boundaries, and surface and mineral ownership at an approved scale.

(b) Maps indicating location of water wells and all other wells, mines or artificial penetrations, including but not limited to oil and gas wells and exploratory or test wells, showing depths, elevations and the deepest formation penetrated within twice the calculated zone of influence of the proposed project. Plugging and abandonment records for all oil and gas tests, and water wells should accompany the map.

(c) Maps indicating vertical and lateral limits of potable water supplies which would include both short- and long-term variations in surface water supplies and subsurface aquifers containing water with less than 10,000 mg/l total dissolved solids. Available amounts and present and potential uses of these waters, as well as projections of public water supply requirements must be considered.

(d) Descriptions of mineral resources present or believed to be present in area of project and the effect of this project on present or potential mineral resources in the area.

(e) Maps and cross sections at approved scales illustrating detailed geologic structure and a stratigraphic section (including formations, lithology, and physical characteristics) for the local area, and generalized maps and cross sections illustrating the regional geologic setting of the project.

(f) Description of chemical, physical, and biological properties and characteristics of the fluids to be injected.

(g) Potentiometric maps at approved scales and isopleth intervals of the proposed injection horizon and of those aquifers immediately above and below the injection horizon, with copies of all drill-stem test charts, extrapolations, and data used in compiling such maps.

(h) Description of the location and nature of present or potentially useable minerals from the zone of influence.

(i) Volume, rate, and injection pressure of the fluid.

(j) The following geological and physical characteristics of the injection interval and the overlying and underlying confining beds should be determined and submitted:

(1) Thickness;
(2) areal extent;
(3) lithology;
(4) grain mineralogy;
(5) type and mineralogy of matrix;
(6) clay content;
(7) clay mineralogy;
(8) effective porosity (including an explanation of how determined);
(9) permeability (including an explanation of how determined);
(10) coefficient of aquifer storage;
(11) amount and extent of natural fracturing;
(12) location, extent, and effects of known or suspected faulting indicating whether faults are sealed, or fractured avenues for fluid movement;
(13) extent and effetcs of natural solution channels;
(14) degree of fluid saturation;
(15) formation fluid chemistry (including local and regional variations);
(16) temperature of formation (including an explanation of how determined);
(17) formation and fluid pressure (including original and modifications resulting from fluid withdrawal or injection);
(18) fracturing gradients;
(19) diffusion and dispersion characteristics of the waste and the formation fluid including effect of gravity segregation;
(20) compatibility of injected waste with the physical, chemical and biological characteristics of the reservoir; and
(21) injectivity profiles.

(k) The following engineering data should be supplied:

(1) Diameter of hole and total depth of well;
(2) type, size, weight, and strength, of all surface, intermediate, and injection casing strings;
(3) specifications and proposed installation of tubing and packers;
(4) proposed cementing procedures and type of cement;
(5) proposed coring program;
(6) proposed formation testing program;
(7) proposed logging program;
(8) proposed artificial fracturing or stimulation program;
(9) proposed injection procedure;
(10) plans of the surface and subsurface construction details of the system including engineering drawings and specifications of the system (including but not limited to pumps, well head construction, and casing depth);
(11) plans for monitoring including a multipoint fluid pressure monitoring system constructed to monitor pressures above as well as within the injection zones; description of annular fluid; and plans for maintaining a complete operational history of the well;
(12) expected changes in pressure, rate of native fluid displacement by injected fluid, directions of dispersion and zone affected by the project;
(13) contingency plans to cope with all shut-ins or well failures in a manner that will obviate any environmental degradation.

(l) Preparation of a report thoroughly investigating the effects of the proposed subsurface injection well should be a prerequisite for evaluation of a project. Such a statement should include a thorough assessment of: (1) the alternative disposal schemes in terms of maximum environmental protection; (2) projection of fluid pressure response with time both in the injection zones and overlying formations, with particular attention to acquifers which may be used for fresh water supplies in the future; and (3) problems associated with possible chemical interactions between injected wastes, formation fluids, and mineralogical constituents.

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